RELATIVE AGE DATING OF AN INLAND DUNEFIELD IN EASTERN LOWER MICHIGAN, USING SOIL DATA

By

Captain Thomas P. Jameson

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF ARTS

Department of Geography

1997

Relative age dating of an inland Dunefield in Eastern lower Michigan, Using Soil Data.

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A variety of inactive sand dunes are present in the Saginaw Lowland of east-central lower Michigan, far inland (> 50 km) from the modern shorezone of Lake Huron. The dunes are parabolic, have northwesterly-oriented limbs, and overlie glacio-lacustrine sediments approximately 12,000 years old. Thus, the dunes must be post-glacial landforms. Using soils data (e.g., morphology, chemistry), Arbogast et al. (in press) suggested that dunes in three fields in the northern and western parts of the region last stabilized between 10 and 4 ka.

This investigation examines previously unstudied dunes in the Deford State Game Area of Tuscola County, located in the southeastern part of the Saginaw Lowland, which could have stabilized concurrently with dunes to the northwest. To test this hypothesis, 19 surface soils (Entic Haplorthods) on dune crests were morphologically and chemically analyzed and compared to the surface soils in the nearby dunefields. Although results suggest concurrent stabilization of the dunes within the Deford area, the data imply that the dunes stabilized before the other lowland dunefields.

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Professor Alan F. Arbogast

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CHAPTER I

INTRODUCTION

Landscapes of unconsolidated sand are especially sensitive to climate change because they are excessively drained and easily mobilized when stabilizing vegetation is reduced and strong winds prevail (Ash and Wasson, 1983; Heidinga, 1984). Dune fields have been identified throughout central and northeastern North America, with dunes in the semi-arid Great Plains anchored by grass (e.g., Ahlbrandt et al., 1983; Muhs, 1985, 1991; Holliday, 1989; Forman and Maat, 1990; Madole, 1995; Arbogast, 1996) and those in the mesic and/or subartic areas stabilized by forest (e.g., Grigal et al., 1976; David, 1979; Filion, 1987,1991; Keen and Shane, 1990; Thorson and Schile, 1995; Arbogast et al., in press).

Although dunes in central and northeastern North America are largely stable at present, periodic mobilization has been demonstrated during the late Quaternary. With no consistent cause or timing for mobilization, these events appear to depend upon local paleoenvironmental variables. Of particular interest are the forested dunes of northeastern North America. Unlike dunes anchored by grass, which mobilize with relative ease in the Great Plains (e.g., Muhs and Maat, 1993; Madole, 1995; Arbogast, 1996), forested dunes require major environmental changes for mobilization to occur. The primary factors associated with mobilization in forested regions in northeastern North America theoretically include: deflation of newly deglaciated or subaerial lacustrine surfaces, devegetation caused directly by Holocene climate change, and devegetation as a result of

fire. A variety of inactive dunes are present in both the upper and lower peninsulas of Michigan (Figure 1:1). Specifically, areas of dunes lie in the Saginaw Bay Lowlands, far inland from the modern shorezone of Lake Huron's Saginaw Bay. In contrast to the more intensively studied coastal dunes along the Great Lakes (e.g., Thompson, 1992; Larson, 1994; Anderton and Loope, 1995), the geomorphic and paleoenvironmental history of these dune fields is poorly understood.

Some soil scientists (e.g., Hutchinson, 1979; Iaquita, 1994), have assumed that these dune fields as former beach ridges of glacial Lake Saginaw, a proglacial lake of the Saginaw lobe of the Laurentide ice sheet. Lake Saginaw existed from approximately 13,000 to 12,000 yrs B.P. (Eschman and Karrow, 1985). Rather than being distinct linear features, as would be the case if they were beach ridges, the landforms consist of individual dunes, parabolic in shape, and have northwesterly-oriented limbs.

In a study by Arbogast et al. (in press), dune fields in the western and northern part of the region were analyzed. In that study, surface soil and wind data were examined. The soils consist of weakly developed spodosols (Entic Haplorthods), suggesting that the dunes last stabilized sometime between 10,000 and 4,000 yrs. B.P. The dunes are oriented to the northwest, indicating that the prevailing winds were northwesterly at the time of mobilization.

This study focuses on dunes in the Deford State Game Area, Tuscola County, which lies in the southeastern portion of the state. In this study, I applied several quantitative, pedologic methods to soils on 19 dune crests. The primary goals of this study were to determine whether the dunes in this dune field have been stable for the same length of

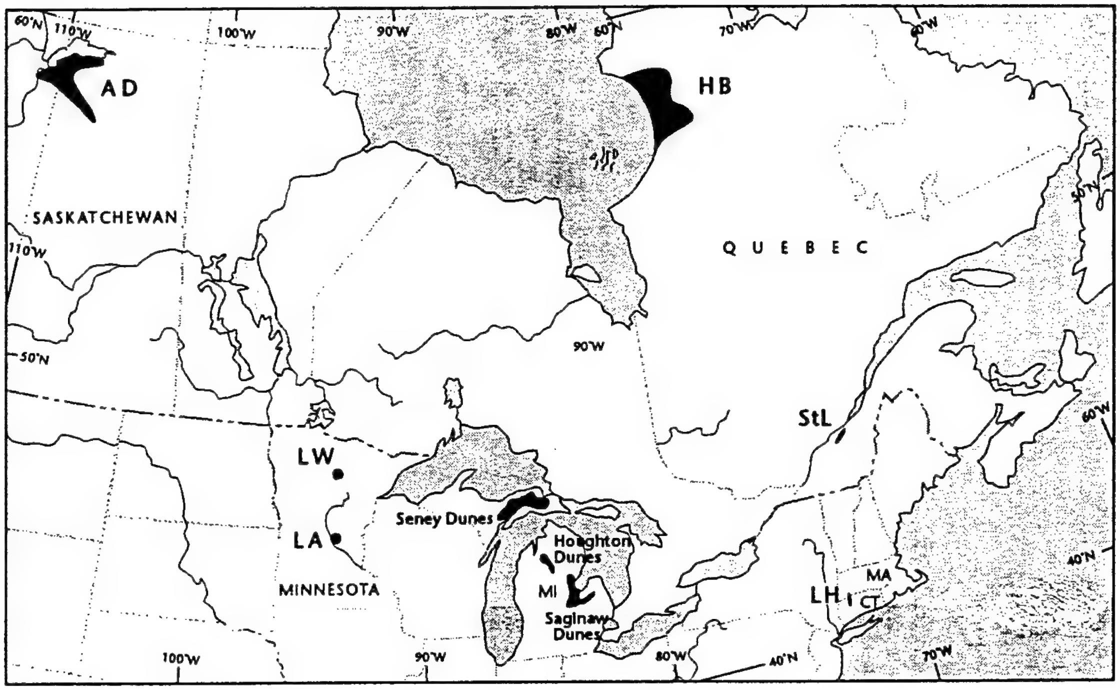


Figure 1 : 1 - Location of forested dunes in northeastern North America. AD, Athabaska dune field; HB, Hudson Bay dune field; StL, St. Lawrence dune field; LH, Lake Hitchcock dune field; LA, Lake Ann; LW, Lake Winnibogoshish. Compiled from David (1981), Filion et al. (1991), Filion (1987), Thorson and Schile (1995), Keen and Shane (1990), Grigal et al. (1976) and Farrrand and Bell (1982). Cartographic services provided by the Michigan State University Cartographic Center.

time, whether this dune field stabilized concurrently with the other dune fields in the Saginaw Bay Lowlands, and if these data can help to better define the paleoclimate record of Michigan.

CHAPTER II

RELEVANT RESEARCH

Eolian Processes and Dune Formation

In order to understand how dunes form, eolian processes must be first examined. Wind blows because of differences in atmospheric pressure. These differences in pressure,(i.e., pressure gradient), occur on both local and global scales and are driven by variations in temperature. Pressure gradients initially force air to move, where it is secondarily affected by Coriolis acceleration (developed from the earth's rotation), vorticity (centrifugal acceleration), and frictional deceleration (Eagleman, 1980). At any given time, wind speed and direction are determined by all of these variables.

Although wind transports sediments in much the same way as water, air is 1,000 times less dense. As a result, the size of the particles it can carry is restricted (Livingstone, 1996). Movement of any particle is resisted by its weight, friction with the surface, and its cohesion (water capacity). The wind speed needed to overcome these factors is called the "fluid threshold velocity" (Summerfield, 1991), and is directly related to the size of the particle. For medium sand (0.5 mm - 0.25 mm) the fluid threshold velocity is 6-7 m s^{-1}. Once particles are mobilized, they subsequently impart motion to stationary particles on the surface through collision. Stationary particles impacted by moving particles will move at an impact threshold velocity, which is 80% of the fluid threshold velocity. This means that particles can be set in motion at a wind velocity that is lower than that required to initiate fluid movement.

Once the fluid and impact thresholds have been passed, particles travel in three ways: creep or traction, saltation, and suspension. These three modes of travel are distinguished by the threshold velocities of the individual particles, with creep occurring at the lowest velocity and suspension at the highest.

In contrast to sand particles, which move primarily by saltation and creep, silt and clay grains are often carried by suspension. Suspension is a function of the balance between the weight of the particle and its drag (Warren, 1976; Livingstone, 1996). The primary deposit associated with suspended sediment is loess, which covers about 10% of the earth's surface. Most loess consists of a thin layer that is incorporated into the existing soils, but some loess deposits are hundreds of meters thick (e.g., Ruhe, 1983; Johnson, 1986; Feng, 1994).

Saltation occurs when particles bounce along the surface (Livingstone, 1996). As the fluid threshold for each particle size is passed, lift forces cause the particles to become airborne. Once airborne, the particles travel downwind with the larger particles tending to quickly descend back to the surface because of their greater weight and associated drag. The height at which most saltating particles travel is dependent of the particle size and wind speed, although most saltating particles travel within 10 mm of the surface (Summerfield, 1991). It is estimated that saltation accounts for four-fifths of all eolian sediment transport (Scott, 1991).

Creep or traction occurs as the saltating particles impact surface particles, rolling and pushing them downwind along the surface. The impact of a saltating grain can be strong enough to move surface particles that are six times larger and more than two hundred

times heavier (Easterbrook, 1993). Creep also occurs as the coarser surface particles, too large to be saltated at a given wind speed, roll into the micro-craters created by the saltating grains (Warren, 1976; Livingstone, 1996). A layer of sand is thus an effective trap for other sand grains due to the loss of energy through collision between grains and the capture of grains in saltation craters. If the trap of sand continues to grow, it will eventually disrupt the flow of air across it, which leads to further accumulation of sand. The critical height to create this disruption of airflow is approximately 30 cm (Easterbrook, 1993).

As the mound grows above 30 cm, it develops a sheltered area of lower wind velocity on the leeward side of its crest (Figure 2:1). As saltating grains encounter the mound they migrate up the windward side or *backslope*. When the grains reach the crest of the dune, they avalanche down the leeward side, or *slip-face*, coming to rest at the angle of repose (McKee, 1966). Thus, movement of the dune occurs as a consequence of deflation on the backslope and deposition on the slip-face.

A variety of dune morphologies exist, and can be classified as being active (free) or inactive (Livingstone, 1996). Free or active dunes are unvegetated and are not anchored by a topographic feature. Common free dune forms are transverse, and parabolic (Figure 2:2). Movement of an active dunes will continue as long as no topographic barriers are encountered and wind velocity, wind direction, the availability of sand, and the cohesion of the sand particles remains favorable (McKee, 1966). Dunes become inactive when sands become immobilized by vegetation or topography. Inactive dunes that have been stabilized by vegetation, without the influence of a topographic barrier, indicate variability of past climates (Scott, 1991).

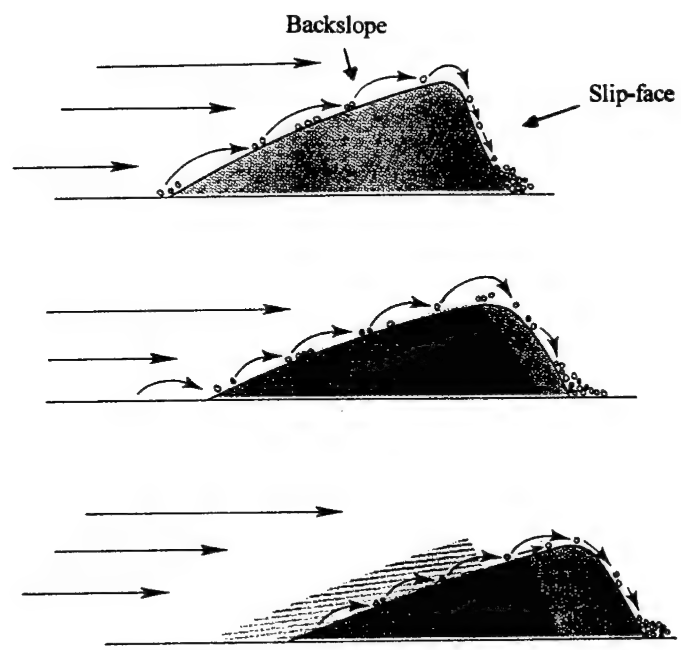


Figure 2 : 1 - The Process of Dune Migration Process (Modified from Doerr, 1990).

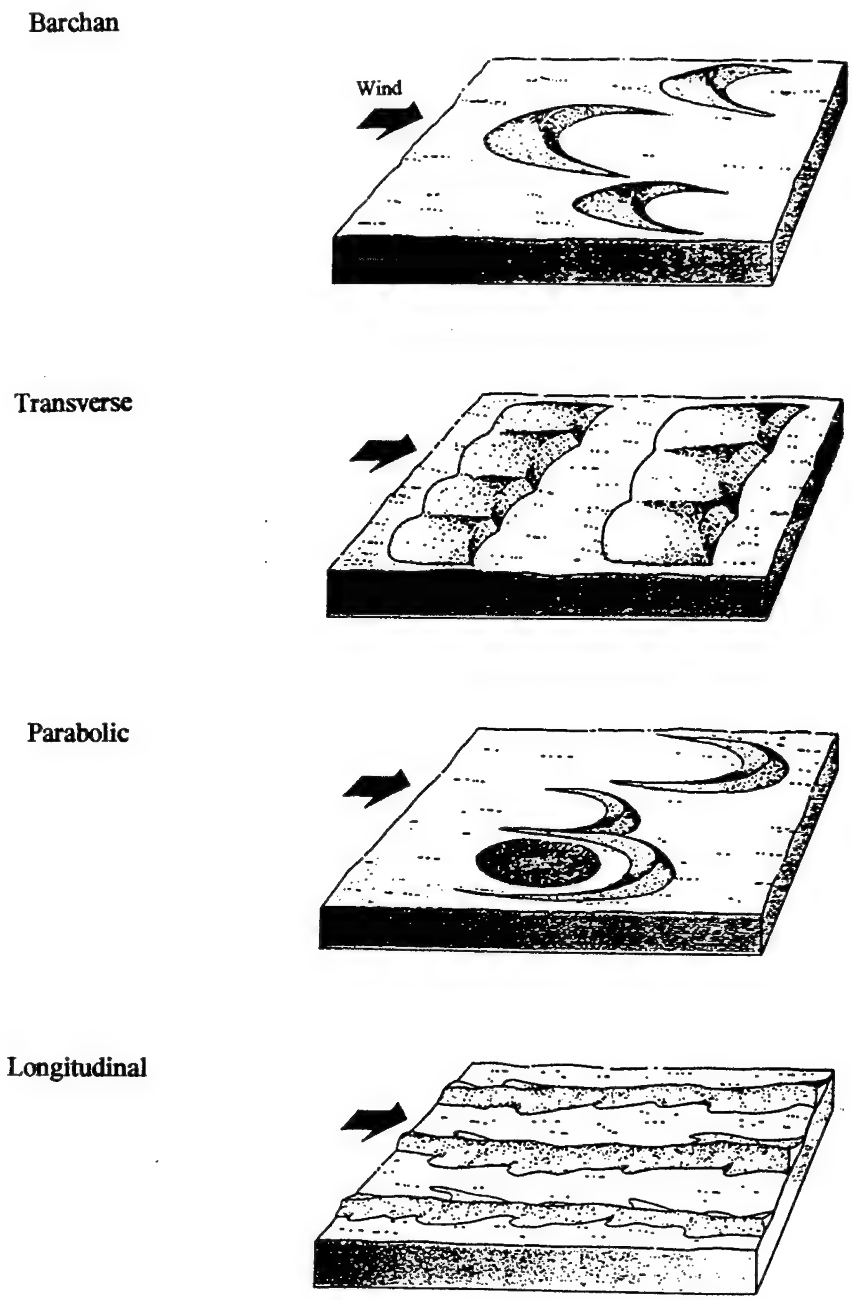


Figure 2 : 2 - Common Dune Forms (Modified from Doerr, 1990).

Parabolic dunes are *u* or *v* shaped, with limbs pointing upwind. It is believed, that parabolic dunes form from blowouts (Summerfield, 1991). Blowouts develop from areas of sand that have been locally devegetated by aridity, fire, flood, high winds, or disturbance by animals, including humans (Livingstone, 1996). Devegetation leads to deflation in the center of the sand patch, while the edges remain anchored by vegetation. As a result, the center of the sand patch is lowered, which in turn may increase erosion because wind is funneled into the area. Erosion proceeds until the blowout is wide enough to diminish the effect of the funneling, where upon plants can reestablish themselves.

Eolian Chronology in the Mid-Continent

Many of the mid-continent's eolian landforms are inherited from late Quaternary (Pleistocene and Holocene epochs) processes. Dated ice cores from the Greenland ice-cap have provided one source of evidence that the late Wisconsin (21,000 - 10,000 B.P.) was 40 times dustier than today (Warren, 1966; Crowley & North, 1991; Livingstone, 1996). The dustiness could have been the result of greater windiness, greater aridity due to changes in precipitation and evaporation, changes in seasonality, decreased vegetation, or a combination of one or all of these factors, due to continental glaciation (Warren, 1966; Crowley & North, 1991).

Some of the relict landforms of that period are the many areas of inactive sand dunes in the mid-continent of North America. Periods of late Quaternary eolian sand mobilization have been reported from a variety of locations in the northeastern and central sections of North America. The relict dunes in these areas differ most markedly in the type of vegetation that is currently stabilizing them. In general, dunes in the semi-arid Great

Plains of North America are stabilized by grasses (e.g., Wright et al., 1985; Forman and Maat, 1990; Muhs, 1995; Arbogast, 1996), while dunes further north and east are stabilized by forest (e.g., Grigal, 1976; Filion, 1987; Keen and Shane, 1990; Thorson and Schile, 1995).

The Great Plains Dune Fields

The Great Plains region of North America is a semi-arid to subhumid grassland stretching from southern Texas, in the south, to the Alaskan arctic. The western boundary is the Rocky Mountains, and the more diffuse eastern boundary extends from Texas in the south to Manitoba in the north. Significant portions of the Great Plains are covered by extensive tracts of eolian sand sheets and dunes, including Texas (Holliday, 1995) Colorado (Muhs, 1985) and Kansas (Arbogast, 1996). The Great Plains also includes the Nebraska Sand Hills which is the largest sand sea in the western hemisphere (Ahlbrandt et al., 1983; Figure 1:1).

Research into late Quaternary eolian sand mobilization on the Great Plains indicates several periods of mobilization and subsequent stabilization. Wright et al. (1985) and Forman and Maat (1990) found evidence that dunes were active during the cool, arid late Wisconsin. Ahlbrandt et al. (1983) reported dune activity in the mid-Holocene, a warm dry period. Most dunes appear to be late-Holocene landforms, however, with eposodic mobilization and stabilization. In northeastern Colorado and Nebraska most dunes mobilized between 3,000 - 1,500 yrs. B.P. (e.g., Muhs, 1985; Ahlbrandt et al., 1983, Muhs and Maat, 1993) which coincides with a period of glacier retreat in the Colorado

Front Range (Benedict, 1973). Most recently, Madole (1995) has documented dunes active in Colorado in the past 1,000 yrs.

In a recent study by Arbogast (1996), radiocarbon dating of buried soils suggests that five periods of late-Holocene stability and soil formation may have occurred in sand dunes on the Great Bend Sand Prairie in southern Kansas. All soils are weakly developed (A/C profiles), indicating brief periods of stability at approximately 2,300, 1,400, 1,000, 700, 500, and 300 yr. B.P. In all likelihood, pedogenesis occurred when climate was more moist. The results of this study, as well as others (e.g., Wright et al., 1985; Forman and Maat, 1990; Muhs, 1995) indicate that dunes can easily remobilize if effective moisture was to decrease (Muhs & Matt, 1993).

Forested Dune Fields

In contrast to the easily mobilized dunes of the Great Plains, a variety of forested dune fields exist in the more humid regions of eastern and north-central North America. Some of these dunes apparently formed as deglaciation progressed, while others evolved as a result of Holocene climate change. Deglacial forested dunes have been reported in Connecticut (Thorson and Schile, 1995), southern Quebec (Filion, 1987), and northern Saskatchewan (David, 1981; Figure 1:1).

The oldest period of eolian sand mobilization near the margin of the Laurentide ice sheet was documented by Thorson and Schile (1995). According to Thorson and Schile, recession of the ice sheet began about 20,000 - 22,000 yr. B.P. throughout New England. An ice recessional lake, Glacial Lake Hitchcock, formed at about 13,000 B.P., when the

Connecticut River watershed was blocked by glaciolaustrine deltas near Middletown, Connecticut. Over the next 4,000 years, as the ice continued to retreat, Glacial Lake Hitchcock expanded northward, eventually becoming the largest ice recessional lake in New England.

A transverse dune, Longmeadow Dune, developed on the eastern shore of the lake between 12,700 and 12,400 years B.P. In their examination of this dune, Thorson and Schile (1995) identified primary sedimentary structures (e.g., suspension and creep deposits, dry avalanching, and planar lamination) that are characteristic of modern inland dunes of arid regions; these structures indicated that the mobilizing winds were northwesterly. To them, such a wind regime suggested a katabatic outflow from the Laurentide ice sheet and are hypothesized to have resulted from a glacial anticyclone (COHMAP,1988). The absence of secondary structures indicated that the dune accreted rapidly (~300 yrs.).

Given changes in sediment composition and thickness in varved sediments from the bottom of Glacial Lake Hitchcock, Thorson and Schile argued that the lake began to drain at about 12,400 yrs. B.P. Subsequently, parabolic dunes formed on the lake bottom sediments. Dune axes indicate that northwesterly winds were responsible for the deflation of the lake bottom sediments. According to Thorson and Schile, this change in wind direction is indicative of the breakdown of the hypothesized glacial anticyclone and its replacement by a wind regime similar to that in the region today.

From approximately 10,500 to 10,000 yrs. B.P., near glacial conditions returned to the region (Younger Dryas climatic interval). As a result, dunes in the Longmeadow area

mobilized. The absence of primary sedimentary structures in these more recent deposits indicates deposition occurred under cold moist conditions. Thorson and Schile found no indications of dune reactivation at Longmeadow in the Holocene.

Another field of stabilized, forested dunes lies in the St. Lawrence Lowland of southern Quebec. The dunes lie to the east and west of the St. Lawrence River, are parabolic, and have northeast to southwest orientations. Some of the dunes directly overlie lacustrine sands and silts, while others bury prehistoric forests and marshes. Initially, these dunes were believed to be littoral (beach) dunes built when the Champlain Sea withdrew at the beginning of the Holocene (Osborne, 1950). In order to establish the geomorphic chronology of the dunes, Filion (1987) obtained 25 radiocarbon dates from wood, peat, and other organics in or buried by the dunes.

Filion argued that the region became subaireal at about 9,500 yr. B.P. with the withdrawal of the Champlain Sea.. Based on dune orientation, northeasterly (anticyclonic) winds are hypothesized to have reworked unvegetated deltatic and marine sands into dunes. Eolian activity in the area ceased at about 7,700 - 7,500 yr. B.P. when very warm and humid conditions stabilized the dunes and the poorly drained interdune areas; the dunes have been stable since that time.

In northern Saskatchewan, a similar eolian environment to that reported by Thorson and Schile (1995) and Filion (1987) apparently existed. In the Athabasca Dunefield, near Cree Lake, a variety of different dune types exist. In a study of dune morphology, structure, and sediments, David (1981) reconstructed the history of these dunes.

The dunes, classified by David as "Cree Lake type dune ridges," lie on gravelly tills and sandy glaciolacustrine deposits. These dunes consist of an individual dune ridge, joined at its downwind end by small parabolic dunes, that are stabilized by vegetation. Primary sedimentary structures within the dunes are similar to those of parabolic dunes. Although David had no radiocarbon control, he uses the orientation of dune sedimentary structures, in conjunction with the deglacial history of the region (Prest, 1969) to reconstruct the eolian chronology.

According to David (1981), the period of eolian activity responsible for creating these dunes began with the deflation of glacial deposits at about 10,000 yr. B.P. During this interval, the ice front was immediately to the east, where a large moraine formed (Prest, 1969). As a result, David (1981) hypothesized that the dune forming winds flowed anticyclonically off of the ice sheet. Subsequently, mobilization ceased approximately 8,800 yr. B.P. when recession of the glacier allowed a southwesterly wind regime to dominate.

In contrast to deglacial forested dunes, forested dunes also activated primarily due to Holocene climatic fluctuations. Research on these dunes has centered in Minnesota. The first was conducted by Grigal et al. (1976), who used soil morphology and radiocarbon dating to analyze dunes exposed along the shore of Lake Winnibigoshish in the south-central part of the state (Figure 1:1). When a dam was constructed in 1884, raising the natural water level by 3 m, wave action began to erode the dunes lying closest to the lake. This erosion exposed the surface soil and a sequence of five buried soils below the surface in the dunes bordering on the southeastern part of the lake.

The basal soil is formed in outwash sediment and has an A-Bs-C profile. Charcoal fragments from the soil yielded a radiocarbon date of about 8,000 yrs. B.P. The five overlying soils all have A-C profiles (Typic Udipsamments), and have similar textures. Organic residue from the 3Ab horizon yielded a radiocarbon date of around 5,000 yrs. B.P. Only the surface soil and the basal soil show measurable levels of Fe, indicative of soil formation under an acidifying vegetative cover.

Overall, the results suggest that a shift from a mesic climate, capable of supporting a stabilizing coniferous forest, to a more arid climate that was dominated by northwesterly winds, at about 8,000 yrs. B.P. Subsequently, the dunes episodically mobilized during periods of relative drought. A return to a more mesic climate, leading to dune stabilization and the formation of the surface soil, occurred sometime after 5,000 B.P. Dune orientation indicates formation of the dunes by northwesterly winds. The current dune field is stabilized by a cover of both *Pinus banksiana* (Jack pine) and *Pinus resinosa* (Red pine).

In a more recent study, Keen and Shane (1990) examined Holocene eolian activity on the Anoka Sand Plain near Lake Ann, in east-central Minnesota. The Anoka Sand Plain is a large area of late Wisconsin outwash (Cooper, 1935). Seven percent of the plain is covered by small fields of parabolic sand dunes. The orientation of these dune fields indicates formation by winds from the northwest. One such dune field lies along the northwest margin of Lake Ann. A presettlement inventory of the vegetation growing on the dunes identified three distinct communities: prairie on the southern slopes, oak forest on the northeast slopes, and wetlands in the inter-dune areas. In order to reconstruct the

chronology of the area, Keen and Shane (1990) retrieved eight cores from the lake bottom sediments and analyzed them for magnetic susceptibility and pollen stratigraphy. Additionally, two radiocarbon dates were obtained from a core taken in the lake's deepest section.

Results indicated that Lake Ann evolved as deglaciation progressed about 11,000 yrs. B.P. During this interval, boreal forest quickly established itself around the lake. Between 10,000 - 9,100 yrs. B.P. the boreal forest gave way to a mixed conifer-hardwood forest, suggesting a warming climate.

Based on dates from the lake cores, the early to mid-Holocene, 9,100 - 4,000 yrs. B.P., the chronology consists of three episodes of eolian activity. Each episode was characterized by drought and an associated shift from forest cover to grasses, an increase in dune mobility, and finally a return of mesic conditions and the re-establishment of forest cover. These episodes transpired between 9,100 - 6,500, 6,500 - 5,100, and 5,100 - 4,000 yrs. B.P.

Overall, Keen and Shane's results compare favorably with those obtained further north in the state by Grigal et al. (1976). Moreover, the results correlate well with the Altithermal (Antevs, 1955), a period of increased warmth and dryness that has been documented throughout the central United States (e.g., Wright et al., 1976; Webb et al., 1983; Baker and Waln, 1985; Baker et al., 1992).

The most recent period of eolian activity in forested dunes of eastern North America was documented by Filion along the eastern shore of Hudson Bay in Quebec, Canada. Unlike forested dunes that activated upon deglaciation or due to Holocene climatic

fluctuations, these dunes apparently activated through a fire-mediated process caused by changes in climatic regime. Two studies by Filion (1984, 1991), have established a Holocene chronology of eolian activity for these dunes. Both studies are based on radiocarbon dating of charcoal and non-charred wood fragments recovered from parabolic dunes that lie on a north to south transect from the tundra through the shrub tundra to the boreal forest.

In the first study, Filion (1984) obtained 82 radiocarbon dates to establish the fundamental chronology of eolian activity in the region. She reported several sequences of stacked paleosols, and argued that many episodes of mobilization and stabilization occurred, which she grouped into three major episodes: 3,250 - 2,750 yrs. B.P., 1650-1050 yrs. B.P., and 750 yrs. B.P. to the present. The frequency of paleosols steadily decreases from the south to the north, suggesting that eolian activity lasted longer in the sparsely vegetated shrub tundra and tundra.

From these results (Filion, 1984), Filion developed a periglacial eolian cycle for the boreal zone. In the proposed model, contrasting temperature-moisture regimes lead to eolian activity that is triggered by fire. The cycle began with a post-Altithermal climatic regime that was cold, dry, and thus more favorable to large forest fires. After a fire, plant recolonization was delayed by these same cold dry conditions. A return to a warmer more humid regime permited plant recolonization, dune stabilization, and soil development. Subsequently, dunes remobilized whenever the climate was sufficiently dry to promote fire.

In her subsequent study (Filion et al., 1991), concentrated on the eolian processes that affected only the forest and shrub tundra zones. Relying on an additional 114 radiocarbon dates, Filion demonstrated that eolian activity was time-transgressive across the study transect. Dune mobilization began in the boreal forest dunes around 6,000 yrs. B.P., whereas dunes in the forest / shrub tundra dunes were stable until about 4,250 yrs. B.P. Finally, the shrub tundra dunes mobilized by 3,900 yrs. B.P. Filion's (1991) chronology correlates well with her previously developed paleoclimatic model (1984).

In contrast to the easily mobilized grassland dunes of the semi-arid Great Plains, the dunes stabilized by forest in northeastern North America apparently require major ecological changes in order to mobilize. From the research conducted to date, three primary ecological changes leading to mobilization are apparent: devegetation caused by fire with a delay in postfire plant recolonization, devegetation caused solely by a change in climate from cool / humid to warm / dry, and the deflation of drift and lacustrine deposits associated with retreating glacial ice.

Podzolization and Spodosols

Podzolization is a soil forming process involving the translocation aluminum (Al), organic matter (OM) and sometimes iron (Fe) which may eventually lead to the formation of Spodosols. Spodosols are soils that contain a spodic horizon which contains accumulations of complex amorphous materials, namely Fe, Al, and OM (Soil Survey Staff, 1975). Spodosols usually have a E horizon, but it is not mandatory to meet the

classification. Currently, two theories exist to explain the process by which Fe and Al translocate.

One theory suggests that Fe and Al move in the soil as soluble metallo-organic chelating (bonding) complexes (Stobbe and Wright, 1959; Peterson, 1976). The process begins with the breakdown of organic matter in the O and A horizons, which produces fulvic (organic) acids that chelate the Fe and Al cations. Because these chelates are water soluble they move downward with the infltrating soil water. These complexes are deposited at depth in the soil due to: (1) changes in the ionic content of the soil solution, (2) increases in the ratio of Fe and Al to fulvic acid, which oversaturates the chelate, and/or by (3) the destruction of the chelate by microbial action.

The second theory of podzolization suggests that chelating complexes are not required to translocate Fe and Al. Instead, Al and Fe, with or without the presence of silicon (Si), can form hydroxy complexes called proto-imogolite (Singer et al., 1978; Wang et al., 1986). These proto-imogolite sols infiltrate with water, and because they carry a negative charge, precipitate upon encountering alkaline conditions at depth, forming a Bs horizon.

Both theories for the formation of spodic horizons depend upon acidic organic matter and sandy parent materials. Organic matter is made up of a wide spectrum of materials ranging from undecomposed plant and animal tissue to humus, and varies considerably in pH (Brook et al., 1983; Birkeland, 1984). Generally, the degree of podzolization declines in a transect from the boreal forest, to the temperate forest, because the litter from conifers is more acidic than that of most broadleaf trees (Schaetzl and Isard, 1991).

Sandy parent materials are more easily acidified because the surface area per unit volume decreases as particle size increases, which allows rapid infiltration of soil water. Sandy soils with their small internal surface areas are not as chemically active as finer textured soils and can quickly be acidified. Therefore, Spodosols commonly form in acidic, sandy, parent materials, which are very common in Michigan.

Schaetzl and Isard (1991) described and explained the geographic distribution of Spodosols in southern Michigan. In Michigan, a floristic tension zone runs diagonally across the lower peninsula. The boundary separates the mixed coniferous-deciduous forests to the north from the predominately deciduous forests of the south. Correspondingly the boundary also separates pedologic provinces (Figure 2:3). According to Schaetzl and Isard (1991), the northern zone is dominated by sandy parent materials and podzolization, while the southern zone is dominated by finer-textured, loamy materials and soil formation by lessivage (clay translocation). Soil maps of lower Michigan show a southern limit to the distribution of Spodosols which roughly coincides with the floristic tension zone (Brewer, 1982), supporting a conclusion that Spodosol development is enhanced under coniferous and mixed forest types.

Schaetzl and Isard employed a functional-factorial approach to derive associations between soils and two of Jenny's (1941) variables: vegetation and climate. Results suggest a linkage between cold-season climate and the podzolization process. In the lower peninsula of Michigan, the strongest Spodosol development occurs in the northwestern section, an area of frequent thick winter snowpacks. Early winter snows insulate the relatively warm soil, preventing the formation of frost within the soil. This

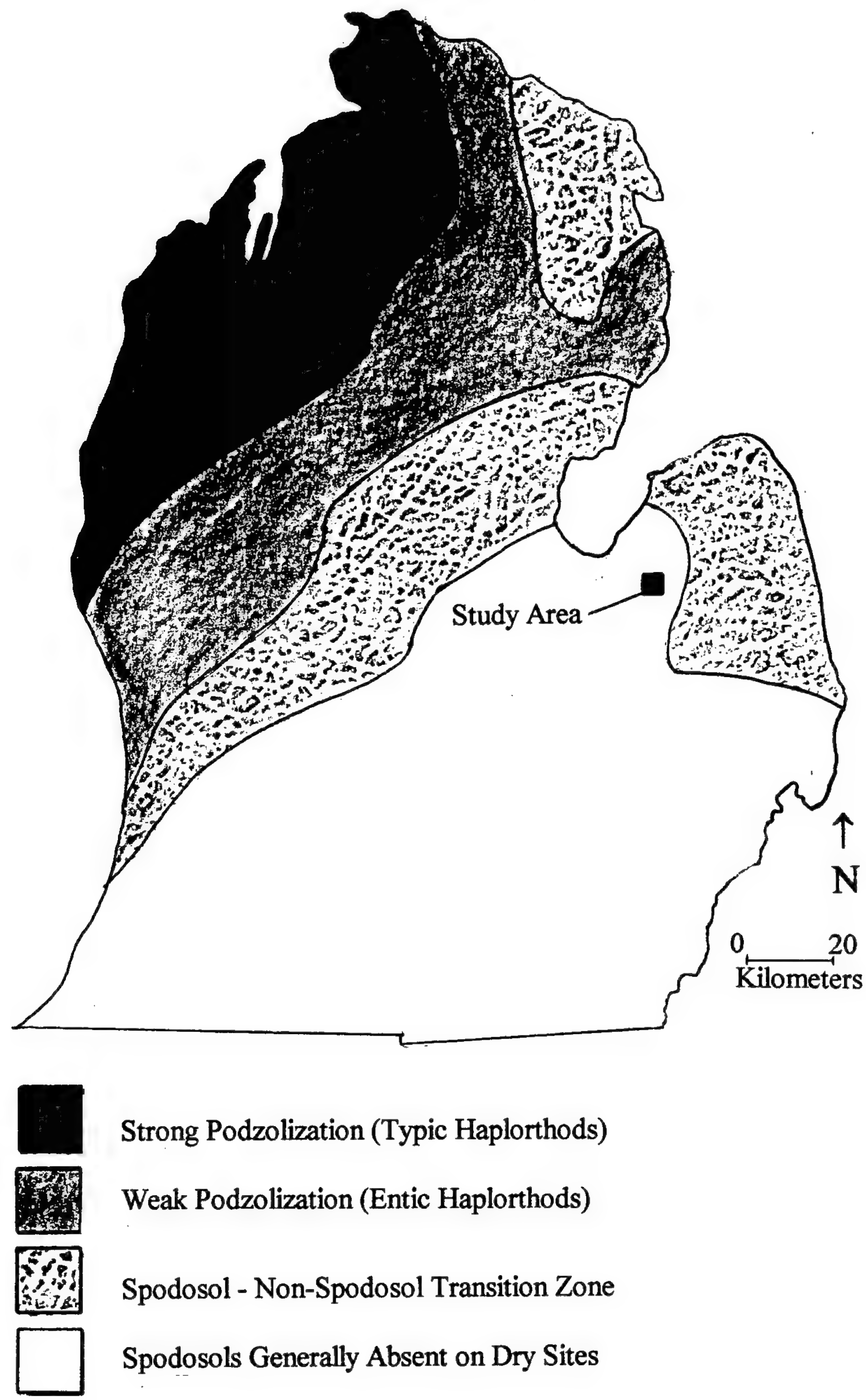


Figure 2 : 3 - Strength of podzolization in lower Michigan (Modified from Schaetzl and Isard, 1991).

lack of soil frost allows for an unimpeded infiltration of meltwater in spring, resulting in translocation of Fe, Al, and OM complexes into the B horizon (Schaetzl and Isard, 1991).

Spodosols as Relative Age Dating Tools

A focus of early work in pedology was the determination of the main variables that define the soil system and the mathematical relationships between soil properties and these factors (Birkland, 1984). As a result, the five factors of climate, organisms, relief, parent material, and time became the standard for defining the soil system. Jenny (1941) developed a functional-factorial model of soil development that established the dependence of soil properties on the five soil forming factors. In practice, the equation is solved by holding four of the factors constant and allowing the remaining factor to vary. In this way the dependency of a single soil property on one soil forming factor can be determined through statistical methods. Geomorphologists often use this same functional relationship to assign a relative age to a surface or deposit. By selecting soils which do not vary in respect to climate, organisms, relief, and parent material, variation in soil properties can be attributed to age.

Soil property indices have been developed that equate soil variation to age. Bockheim (1980) selected 32 chronosequences from previous research to develop chronofunctions, correlating changes in soil properties with changes in the five soil forming factors Jenny (1941). The chronosequences were from soils across the globe, ranging in age from 0-500 yr. B.P. to ≥ 1,000,000 yr. B.P. The study identified trends in soil development with time, with most soil properties continuing to change, even with the passage of 10 million years. Climate and parent materials played important roles. Solum thickness, oxidation depth,

and clay content in the B horizon increase with increasing annual temperature. Rates of increase in clay content of the B horizon and solum thickness were positively correlated with the content of clay in the parent material, implying that parent material uniformity is crucial when examining chronosequence data. Soil pH decreased with time independent of climate, parent material, and biotic factors.

Relative dating using soils has been effectively demonstrated in Oregon. Parsons et al. (1970) used seven geomorphic surfaces of known age in the Willamette Valley, Oregon to illustrate how soil development can be used as a relative age indicator. Over five hundred soils were initially described on a west to east transect across the valley. Seven soils, each representative of the seven major valley surfaces, were further analyzed. Radiocarbon dating of three of the surfaces, published in other studies (Balster and Parsons, 1968, Reckendorf and Parsons, 1966), provided absolute dates for the surfaces. Results showed that as the soils aged, organic matter and base saturation (pH) decreased with depth, and B horizons became thicker and more clay rich.

In California, Swanson et al. (1993) utilized morphologic and chemical (Fe, Al) properties of Bs horizons to date a series of recessional and end moraines in the White Mountains. In these soils, morphologic properties such as profile depth, horizonation, color and texture could not discriminate between late Wisconsin deposits, but were capable of discriminating between late Wisconsin and the older Pleistocene deposits. Of the four Fe and Al extraction parameters, only F_{cd} (Fe extracted by sodium citrate-dithionite), showed a consistent relationship with age. Swanson's data show that soil and weathering properties can be employed to define relative chronologies.

Franzmeier and Whiteside (1963a) examined a chronosequence of soils developed on three sandy lake terraces and a moraine in northwestern lower Michigan (Cheboygan and Emmet Counties). The terraces resulted from fluctuating water levels in glacial Lake Michigan during the Late Wisconsin and Holocene. The parent material of the terrace soils is excessively-drained lacustrine sands, which are covered by second-growth coniferous and mixed deciduous forest. The study transect extended from the Algoma terrace (2,250 yrs. B.P.), close to the modern shorezone of Lake Michigan, through the Nipissing (4,000 yrs. B.P.), the Algonquin (8,000 yrs. B.P.), and to the Valders moraine (10,000 yrs. B.P.).

Soil samples were obtained from a single pit dug into the crest of each surface. Fe and Al were extracted from all sampled horizons using sodium dithionite-citrate-bicarbonate. Data derived form these extractions suggested that the content of Fe and Al in the B horizons increases with increasing age. When compared to the chemically determined class boundaries for spodic horizons (Soil Survey Staff, 1960), a Bs horizon required a minimum of 3,000 years to develop while the development of a Bhs horizon required 8,000 years.

A study by Barrett and Schaetzl (1992, 1993) reexamined the chronosequence studied by Franzmeier and Whiteside (1963a,b). Barrett and Schaetzl examined the sandy soils that developed on the four lake terraces: Algonquin, Battlefield, Nipissing, and Algoma, and assigned ages to each terrace based on the center of age ranges found in the literature: Algoma: 3,000 yrs. B.P., Nipissing: 4,000, Battlefield: 10,000, and Main Algonquin: 11,000.

Extractions of Fe and Al were taken for each soil horizon in sodium citrate-dithionite and acid ammonium-oxalate. Results suggest that Fe and Al have been translocated from the upper horizons to the B horizons of these soils. Weighted B horizon means were used to reflect soil development, and ratios of soil development were regressed against terrace surface age to create numerical chronofunctions. Like Franzmeier and Whiteside (1963), Barrett and Schaetzl concluded that at least 4,000, but less than 10,000 years are required for the development of a spodic horizon in northwestern lower Michigan.

A study by Arbogast et al. (in press), closely related to this study, employed soil development and a single radiocarbon date as age indicators for thirty inland dunes in east-central Michigan. The dunes are parabolic with northwest oriented limbs, and lie on flat wet landscapes. Because these dunes mantle the glaciolacustrine sediments of glacial Lake Saginaw and the adjacent outwash plain of the Port Huron moraine (Leverett and Taylor, 1915; Eschman and Karrow, 1985), they had previously been confused by soil scientists with beach ridges (e.g. Hutchison, 1979; Iaquita, 1994). Hypothetically, the dunes could be deglacial (e.g., David, 1981; Filion, 1987; Thorson and Schile,1995), forming immediately after the region became subaerial (approximately 12,000 B.P.), a result of Holocene climate change (e.g.s, Grigal et al., 1976; Filion, 1984,1991; Keen and Shane, 1990), or they may have evolved sometime in between.

Dunes were identified, through the use of air photos, along a north/northeasterly transect that extended from Gratiot County through Midland County, to Arenac County. Ten dunes were selected for study in each county. Pits were excavated into the crests of each dune, the soils were described, and samples of each horizon were collected for

laboratory analyses. In order to determine the direction of dune-forming paleowinds, sand roses were constructed for dunes in each county.

Results of the study showed that the soils were similar in morphology, both within and between the dune fields. Parent materials were uniform. Statistically significant differences did not exist between the dune fields with regard to Fe and Al content, solum thickness, and POD index.

In an effort to estimate the relative age of the dune fields, soil chemical data were compared with soils of known age in NW lower Michigan (Franzmeier and Whiteside 1963b; Barrett and Schaetzl, 1992) where podzolization is more intense. Results of this research suggest that the dunes in east-central Michigan stabilized before 4,000 yrs. B.P., but perhaps after 10,000 yrs. B.P.

A similar study by Arbogast (unpublished data) examined soils in a stabliized dune field perched on a hypothesized Nipissing terrace (Farrand and Drexler, 1985) along the southern shore of Lake Superior. In order to estimate the age of the dunes, surface soils were analyzed on 13 dune crests. All pedons consisted of A/E/Bhs/Bs/C profiles. Extractions of Fe and Al were obtained for some soil horizons and compared to the extraction data of Barrett and Schaetzl (1992) for soils on lake terraces of known age in northwest lower Michigan. According to Arbogast (personal comm.) the comparison of the extractions suggested that the dunes stabilized at the end of the Nipissing Transgression, about 5,000 yrs. B.P.

Many pedons that morphologically appear to be Spodosols do not meet the strict chemical criteria set forth by the Soil Survey Staff (Schaetzl and Mokma, 1988). This

discrepancy has led to problems for the soil mapper who relies on morphologic criteria for quick soil identification in the field. In order to partially address this dilemma, a numerical index of soil development, the POD index, was developed by Schaetzl and Mokma (1988). This index is determined solely from morphologic criteria and provides a formula to quantify development in Spodosols in the field. The index assumes that the following morphologic changes are produced by pedogenesis: E horizons become whiter in color, B horizons become redder and darker, and the number of B sub-horizons will increase.

To test the index, Schaetzl and Mokma first applied it to 379 representative Spodosol pedons from county soil surveys of the northernmost United States. Subsequently, the index was tested against 344 Spodosol-like pedons, from outside of the United States. Results roughly indicate POD index limits of 0-2 for non-Spodosols, 2-6 for Entic Haplorthods, and ≥ 6 for Typic Haplorthods. Additionally, a mathematical relationship between POD index and time was implied, with podzolic development theoretically increasing at a steady or accelerating rate. Since the development of the POD index, several studies have correlated POD values with age.

Barrett and Schaetzl (1992, 1993) calculated POD values for northwestern lower Michigan, lake terrace pedons. For example, the Algoma (3,000 yrs. B.P.) and Nipissing (4,000 yrs. B.P.) pedons yielded POD values of 0, while the Battlefield (10,000 yrs. B.P.) had a value of three and Algonquin (11,000 yrs. B.P.) seven. These values correlated nicely with the chemical data which suggested that the dunes stabilized sometime in the middle Holocene.

In east-central lower Michigan, where podzolization is weaker (Schaetzl and Isard, 1991), Arbogast et al. (in press) reported that mean POD indices for the dune fields were very low (Arenac 0.4, Midland 0.4, Gratiot 0.0). These consistent low values supported the chemical data, which suggested that the dune fields may have stabilized simultaneously in the early or middle Holocene. In the perched dune field along Lake Superior, examined by Arbogast (unpublished data), POD indices ranged from 4 to 5.

CHAPTER III

STUDY AREA

The study area is located in the Deford State Game Area of Tuscola County, which lies in the eastern portion of Michigan's lower peninsula, 50 km east-northeast of the city of Saginaw. The game area encompasses 65 km^2. of state property, interspersed with commerical and privately owned holdings. In general, most of the larger expanses of well drained soils are privately owned. It is bordered by the Cass River to the North, Riley Road to the South, the town of Deford to the East, and the town of Caro to the West (Figure 3:1).

Geology

Pre-Quaternary geology of the study area is dominated by Mississippian sandstones, limestones, and shales (Eschman, 1985). With the commencement of Pleistocene glaciation, the region experienced a complex sequence of glacial advances and retreats. The earliest recognized advance, which reached the southern borders of Ohio and Indiana, occurred during the Pre-Illinoian (730,000 B.P.). With the possible exception of the Sydney Interstadial, Michigan probably remained buried under the ice through the Early Wisconsin (55,000 yrs B.P.; Leverett and Taylor, 1915; Eschman, 1985; Eschman and Karrow, 1985).

The most recent glaciation of the study area occurred during the Late Wisconsin (Table 3:1). From 24,000 yrs B.P. to about 10,000 yrs B.P. a complex sequence of glacial

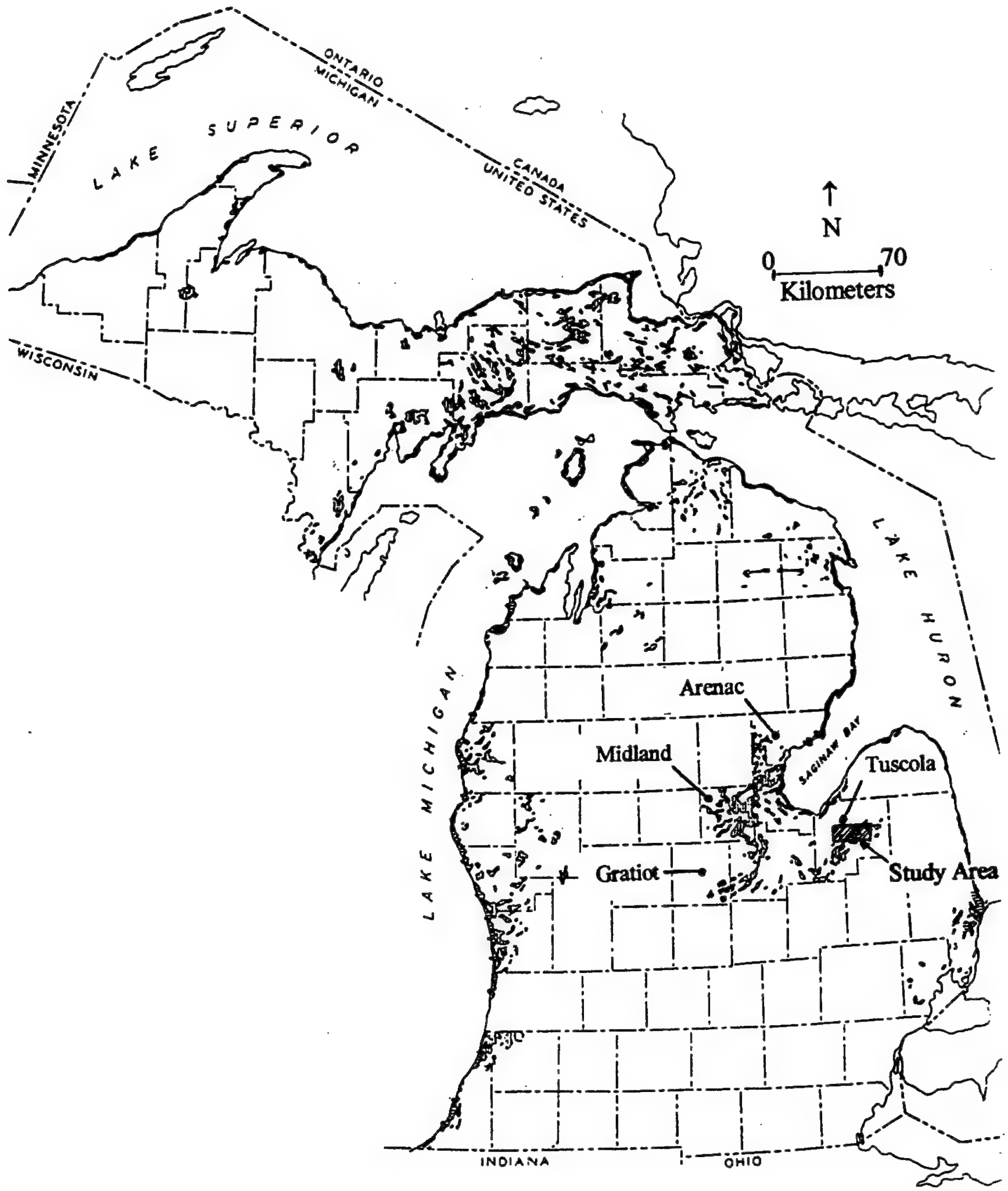


Figure 3 : 1 - Location of Study Area and other Inland and Coastal Dunefields in Michigan. Fields studied by Arbogast et al. (in press) are highlighted, as is the Tuscola dune field under study here. (Modified from Santer,1993)

Table 3 : 1 - Chronology of the Wisconsin Glacial Stage (Modified from Dreimanis and Karrow, 1972).

Holocene

______________________________10,000 B.P

Late Wisconsin

Greatlakean Substage ------------------------11,000 B.P.
Twocreekan Interstadial
Port Huron Substage--------------------------13,000 B.P.
Port Bruce Substage--------------------------15,500 B.P.
Erie Interstadial
Nissouri Substage---------------------------- 21,000 B.P.

______________________________ 24,000 B.P.

Middle Wisconsin

______________________________ 55,000 B.P.

Early Wisconsin

______________________________ 110,000 B.P.

advances and retreats transpired in the region. As a result, a series of proglacial lakes developed in the region (Eschman and Karrow, 1985). Germaine to this study are the events that occurred since final deglaciation of the study area.

At approximately 14,500 yrs B.P., the study area became ice free. Subsequently, in the Port Huron stadial, around 13,000 yrs B.P., ice readvanced to a position immediately to the north of the study area. During that time, Lake Whittlesey (225m) was present in the Erie Basin (Eschman and Karrow, 1985). For the next two hundred years, Lake Whittlesey drained westward across the thumb, via the Ubly outlet into glacial Lake Saginaw (212m), where it ponded before flowing through the Grand River valley into glacial Lake Chicago (Figure 3:2; Eschman and Karrow, 1985). At this point, the study area was submerged as waters of glacial Lake Saginaw reached the Ulby outlet delta at Cass City, 10 km to the northeast (Figure 3:3). As the Port Huron ice began to retreat, the Ubly outlet was abandoned and several progressively lower outlets opened across the thumb, north of Ulby. Lake Saginaw receded from the Cass River valley around 12,800 yrs B.P., and the study area subsequently became subaerial. Neither the subsequent Late Wisconsin glacial advances and their associated changes in lake levels, nor the Holocene lake level changes, covered the study area with ice or water. In all probability, the Cass River has occupied the valley since deglaciation.

The dunes in the Deford State Game Area lie in the Cass River valley between the Juanita Moraine to the east and the Port Huron moraine to the west, and overlie glaciolacustrine sediments (Leverett and Taylor, 1915). The dunes have maximum slopes of 6 to 12 percent and are generally less than three meters high.

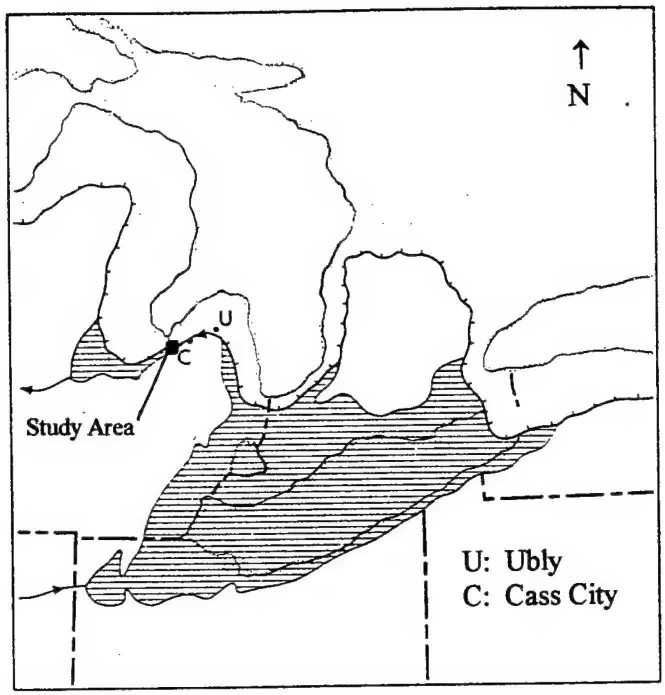
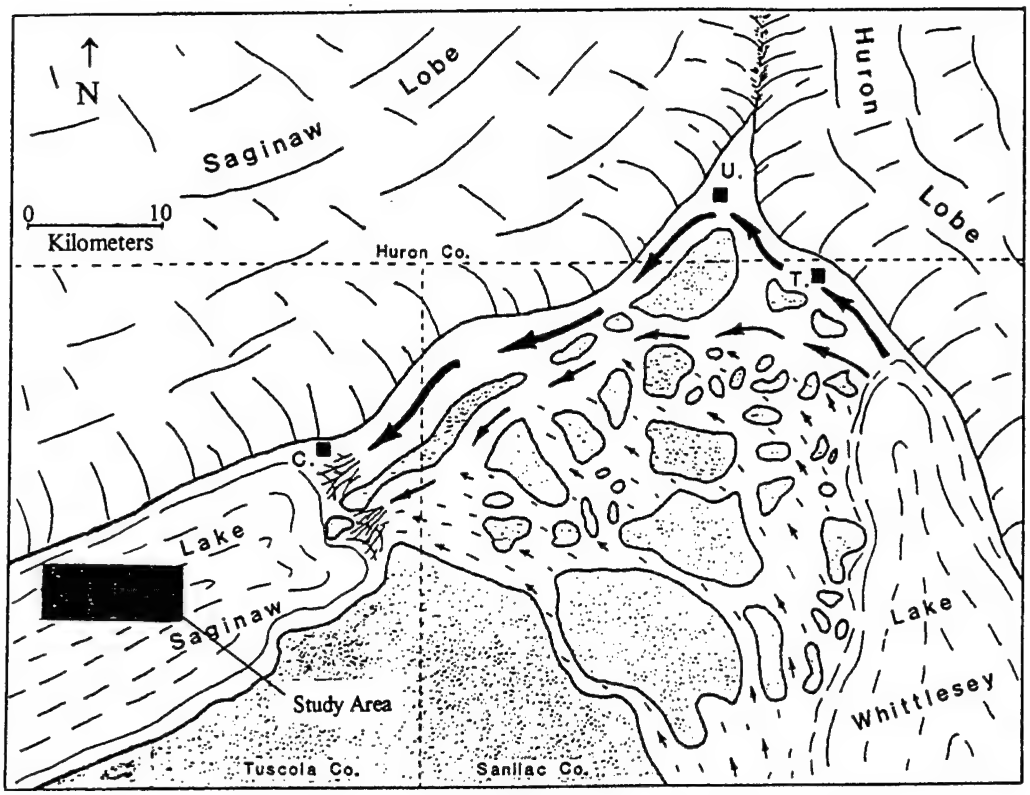


Figure 3 : 2 - Glacial Lakes Whittlesey and Saginaw (Modified from Eschman and Karrow, 1985).



C: Cass City U: Ubly T: Tyre

Figure 3 : 3 - The Ubly outlet of glacial Lake Whittlesey (Modified from Winters et. al, 1985).

Soils

Surface soil morphologies on dunes in the study area have largely resulted from podzolization. The dunes contain Covert series soils classified as mixed, mesic Alfic Udipsamments, and Ottokee series soils, sandy, mixed, mesic Entic Haplaquods, while the somewhat poorly and poorly drained areas that lie between the dunes contain Wixom - Belleville and Pipestone soils; sandy, mixed, mesic Typic Haplaquolls and sandy mixed, mesic Entic Haplaquods (Mettert, 1986).

Climate

The present climate of the study area reflects its easterly location on the peninsula. The climate is modified by winds from the west, which cross Lake Michigan and pick up warmth and moisture in the winter, and cool, moist air in summer (Feenstra, 1979). The resulting climate is warmer and more moist than those of similar latitudes in Wisconsin and Minnesota. The closest weather station to the study area is in Caro. Mean annual temperature (1940-1969) at Caro is 8.3° C, with July and January temperatures averaging 21.3° C and -5.5° C respectively. The average growing season (# of days between last frost in spring and first frost in fall) is 126 days. Mean annual precipitation is 71.3 cm, with the highest monthly average occurring in July (7.8 cm). February is the driest month (3.2 cm). Mean annual snowfall is 86.6 cm. On average, 61 days of the year have at least 2.54 cm of snow on the ground.

Vegetation

The landscape within southern Michigan was primarily forested before European settlers arrived from New England in the mid-nineteenth century (Bowman, 1986). Pre-settlement vegetation within the study area was dominated by a mixed coniferous-deciduous forest assemblage. Based on logging records, nearly pure stands of *Pinus strobus* (white pine) dominated the dry soils, while broadleaf species, *Acer saccharum* (sugar maple) and *Quercus* (oak), dominated the poorly drained areas (Mills, 1918). Current vegetation within the study area consists primarily of second growth deciduous forest. Common tree species in the study area are *Quercus rubra* (red oak), *Quercus velutina* (black oak), *Pinus strobus*, *Acer saccharum*, *Acer rubrum* (red maple, *Populus tremuloides* (trembling aspen) and *Ulmus spp.* (elm) (Mettert, 1986).

Cultural History

The earliest known inhabitants of Tuscola County were two Ottawa Indian tribes, the Suak and the Onottawas, who resided in the area in the 1500's (Mills, 1918). The word "saginaw" literally means land of the Sauk. These tribes subsisted through hunting and gathering. The Onottawas established their principal village on the Cass River near Bridgeport, approximately 50 km southeast of the study area. The Sauks and the Onottawas were eventually displaced in a fierce tribal war with the Chippewas, who controlled land west and south of Lake Superior.

The first Europeans in the area were fur traders, arriving around 1816. The entire Saginaw Lowland remained in Chippewa hands until the signing of the Treaty of Saginaw

in 1819, which was negotiated by General Lewis Cass (Mills, 1918). The provisions of the treaty left the Chippewa many tracts of land along the rivers of the Huron watershed, but no tracts along the Cass River.

Although the treaty opened up large portions of lower Michigan for settlement, immigration to the Cass River valley occurred slowly. These early settlers were aware of the vast pine forest throughout the region, but did not comprehend its value because it was mistakenly believed that the forests of Maine could satisfy all the demands of the industrializing East (Mills, 1918).

By the 1840's, lumber camps had been established in the region. The first logging camp in the vicinity (≤ 5 km) of the study area was established along the Cass River at Caro in 1847. The county was platted in 1850, separating it from Saginaw County to its west (Romig, 1973). The logging boom on the Cass River continued for the next 40 years, and was second only to that in the Titabawassee River valley. The Cass River basin held "the finest growth of cork (white) pine timber in the United States (Mills, 1918)." The basin yielded 1,126,000,000 board feet of pine, with the largest output in a single year of 104,458,000 board feet occurring in 1873. Large scale lumbering ceased in the valley by 1880.

In the wake of the timber boom, agriculture expanded in the county, focusing on corn and wheat production. In 1871 an extensive period of severe drought was followed by a regional forest fire, causing massive erosion. As a result, the Tuscola County Soil Conservation District was organized in 1943. Drainage tiles and canals have drained the landscape such that mechanized farming and logging of the area remains profitable.

Present day land-use in and around the study area is dominated by commercial farming and logging, with 69% of the county's total land area devoted to agriculture. Corn, dry beans, wheat, sugar beets, and soybeans are the major crops. As a result, the majority of the dunes in the Tuscola County dune field now lie on privately owned property. The dunes, with their well drained soils, are virtually the only high ground in the valley. Thus, they are favored locations for homes and businesses. In addition, the dune sands are also a valuable construction material, and based on my observations many dunes have been completely destroyed through mining.

CHAPTER IV

METHODS

Both field and laboratory methods were used in this study. The basic premise of these methods is that soil forming factors, other than time (i.e., climate, organisms, relief, and parent material), are similar between the individual dunes in the study area , as well as between the previously identified dunes in Gratiot, Midland, and Arenac Counties. I assumed that dunes with soils that have similar morphologies have comparable ages.

I confined my study to dunes that lie within the Deford State Game Area (Figure 4:1). This area of public land is one of only two areas in the entire dune field where a sizable population (< 20 dunes) of undisturbed dunes exists. Sample sites were identified by comparing USGS topographic maps and aerial photos with the modern county soil surveys. Landforms that rose one or more contour intervals (1.5 to 3 meters) above the surrounding topography were compared with the soil survey to determine whether they were sandy. Through this process 31 potential study sites were identified.

Field Methods

Only 28 dunes were analyzed in the field, because 3 of the potential study sites had been destroyed through mining. Once on site, the crest of the dune was located. Theoretically, the crest provides a relatively flat sample area that is less susceptible to erosion, thereby insuring that the variable of relief remains constant.

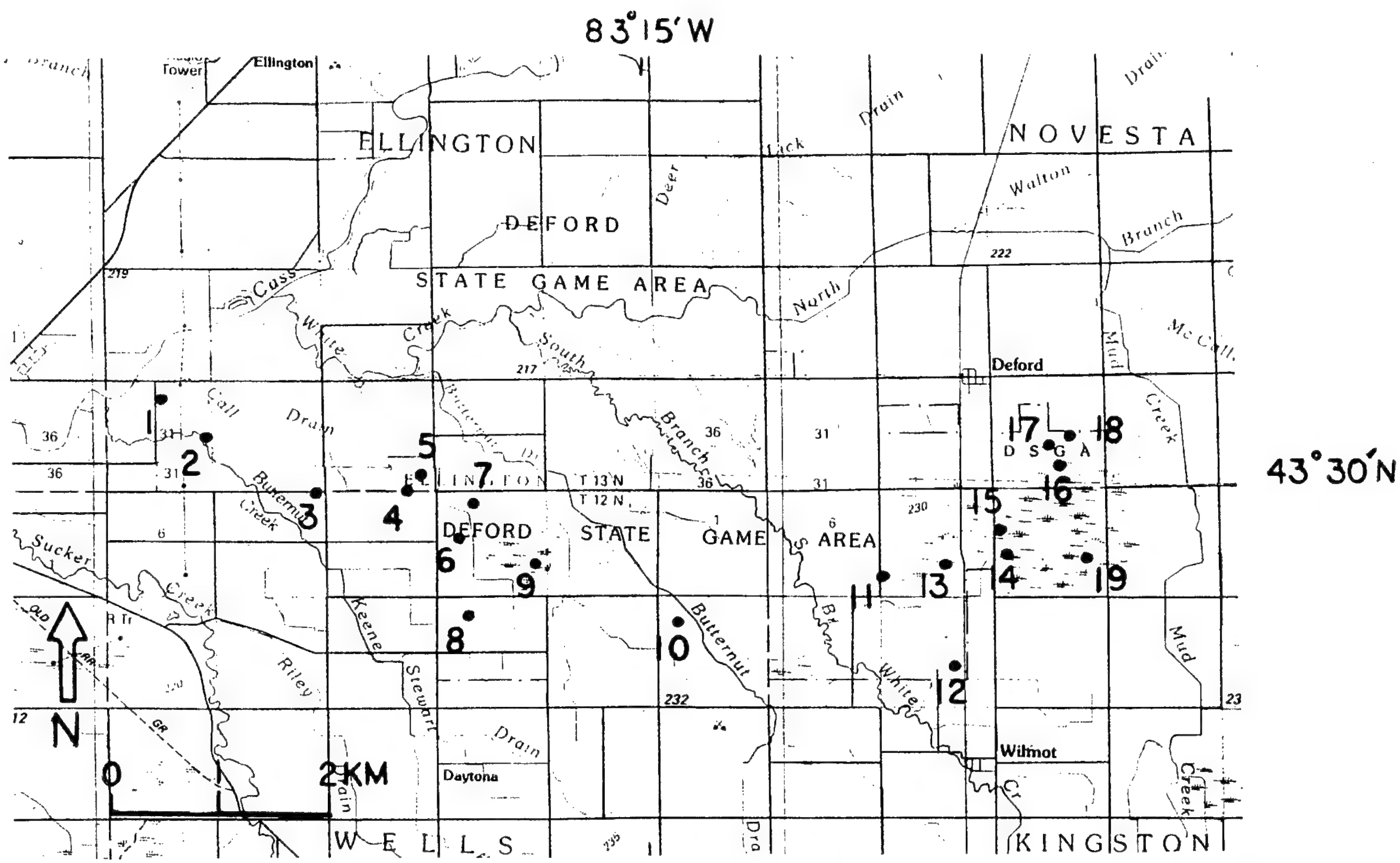


Figure 4 :1 - Study Area (Modified From U.S.G.S. Flint, Michigan 43083-A1-TM-100, 1:100,000, 1990).

● = SAMPLED DUNE

Observable geomorphic characteristics of each sample site, such as vegetative cover, slope, and potential disturbance by erosion and/or human impact, were carefully examined to assure soil uniformity. As a result, nineteen dunes met the specified criteria for continued study (Figures 4:1, 4:2, 4:3, 4:4, 4:5). Pits were excavated by hand at the crest of each dune from the surface down through the base of the solum, and the exposed profile was described using the standard terminology (Soil Survey Manual, 1993). Subsequently, bulk samples of approximately 400 grams were collected from each soil horizon.

Laboratory Methods

Munsell colors were determined on field-moist samples, under a fluorescent light in the laboratory, by myself and another person working independently. Soil samples were then oven dried at 60° C for three hours, and passed through a 2 mm sieve. All samples were then split using a series of sample splitters to 30 grams, which were subsequently used for all further lab analyses (Soil Survey Staff, 1993).

Two chemical extractions from soils were used as aids in identifying forms of Fe and Al. Extraction by sodium-citrate-dithionite is thought to remove the total free Fe and Al that is not included in the structure of silicate minerals. Free Fe (Fe_d) and Al (Al_d) can exist as crystalline oxides, amorphous oxides, and bound to organic complexes (chelates). Many researchers doubt that Al_d is equivalent to "free Al," and thus has no meaning (Schaetzl, personal comm.). Extraction by ammonium-oxalate can identify active Fe (Fe_o) and Al (Al_o) which can exist as amorphous oxides, and organic

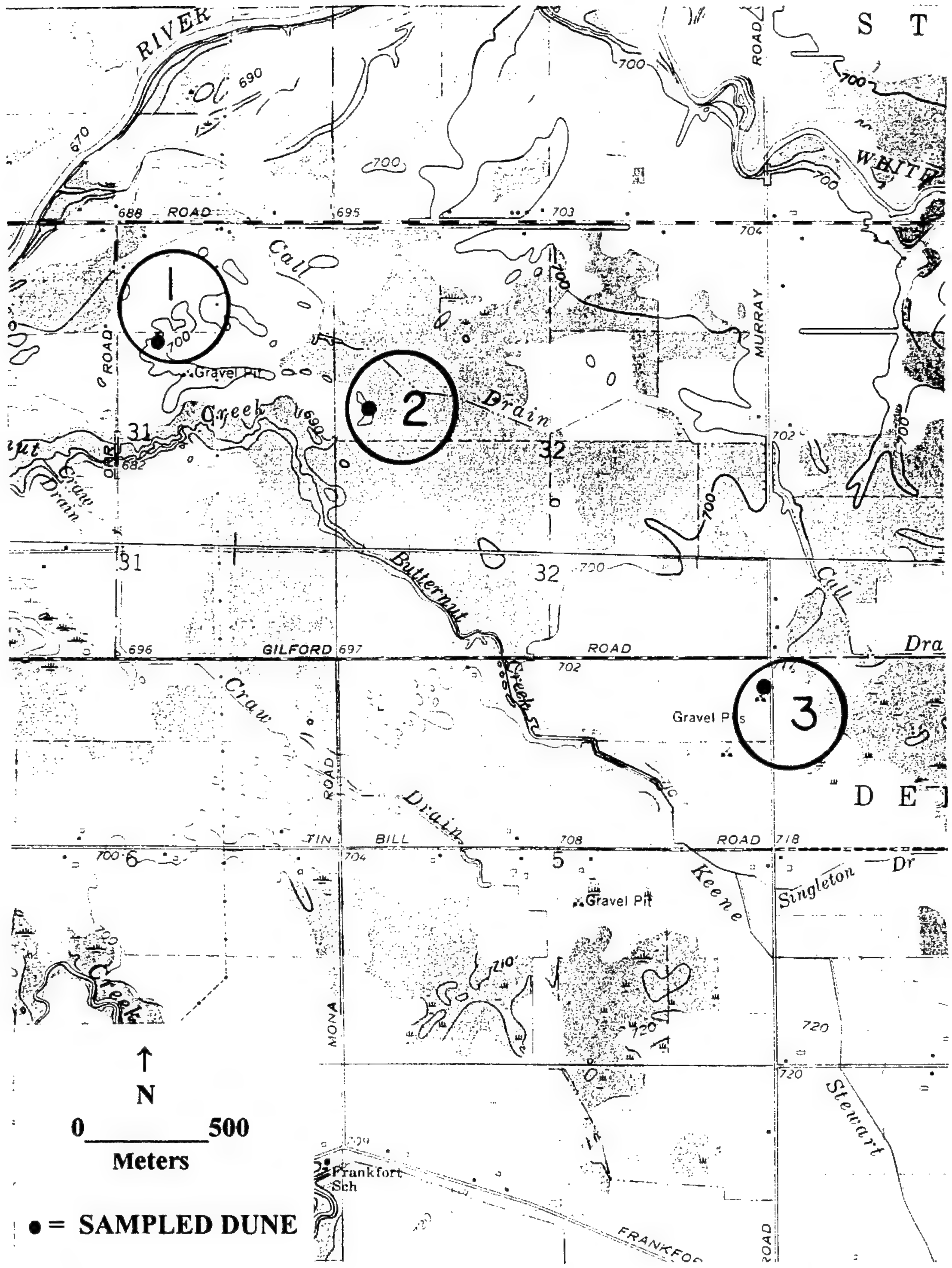


Figure 4 : 2 - Detailed Study Area - Pits 1,2,3 (Modified From U.S.G.S. Ellington, Mich., 1:24,000, 1963).

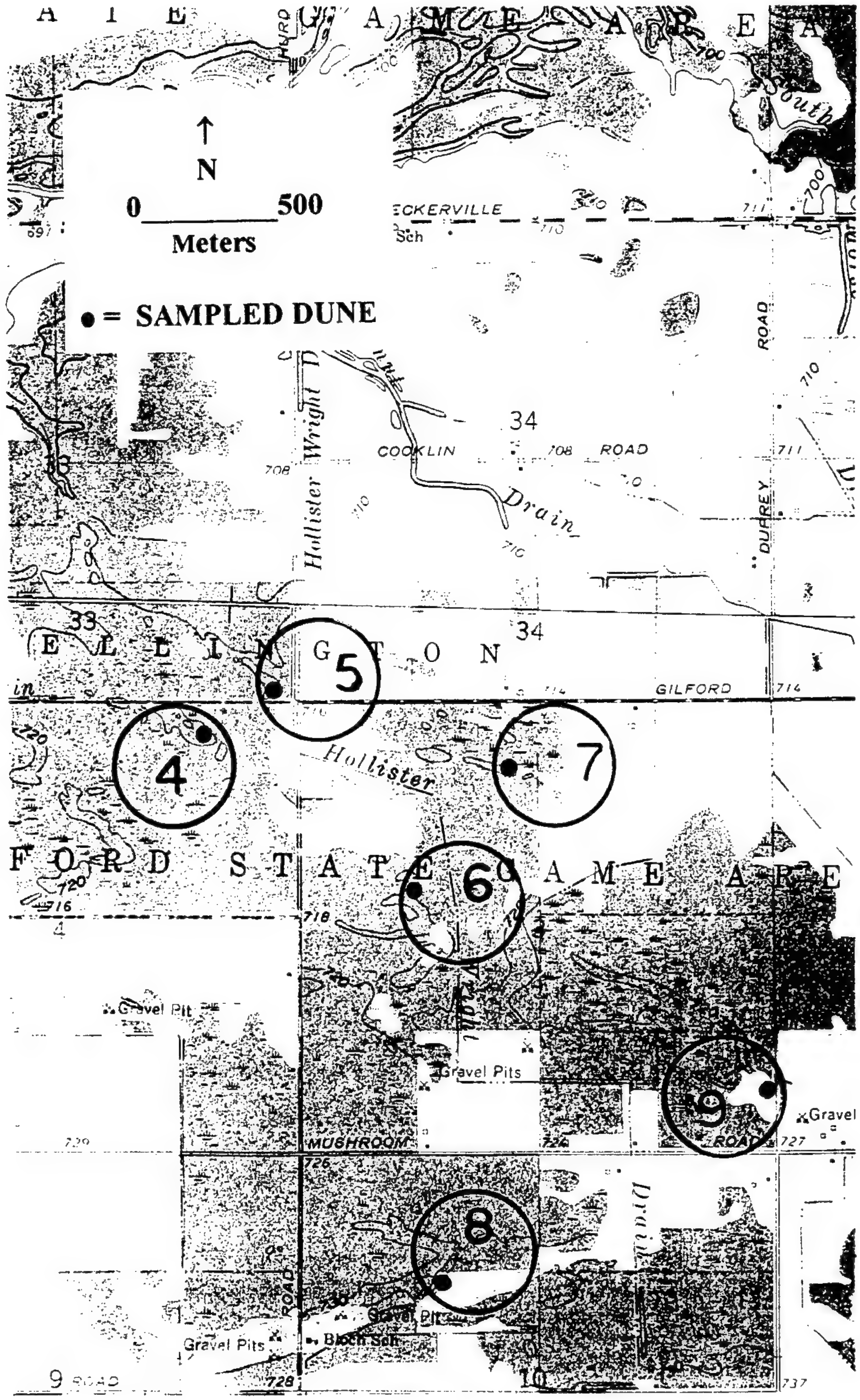


Figure 4 : 3 - Detailed Study Area - Pits 4,5,6,7,8,9 (Modified From U.S.G.S. East Dayton, Mich., 1:24,000, 1963).

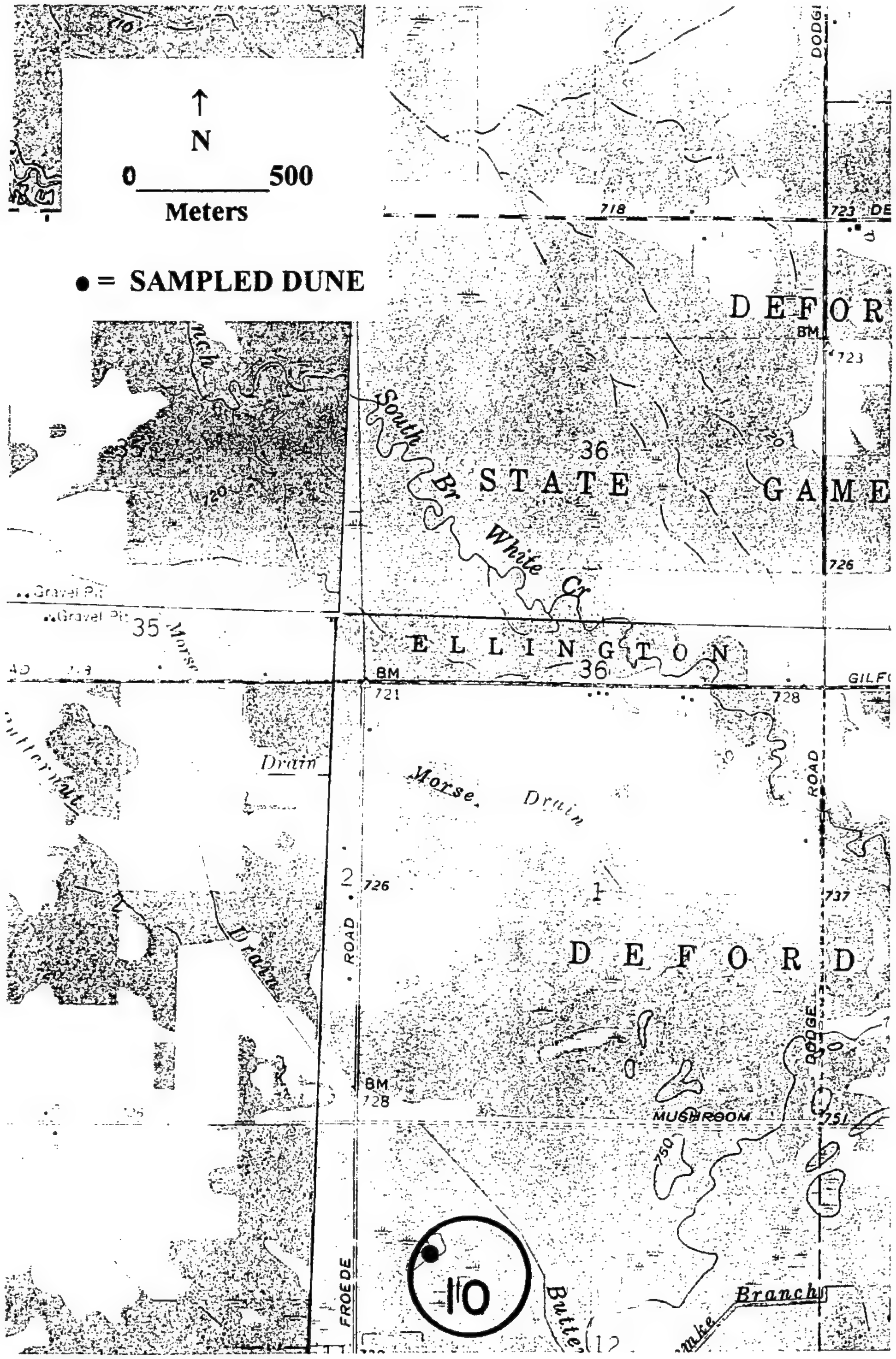


Figure 4 : 4 - Detailed Study Area - Pit 10 (Modified From U.S.G.S. Kingston, Mich., 1:24,000, 1963).

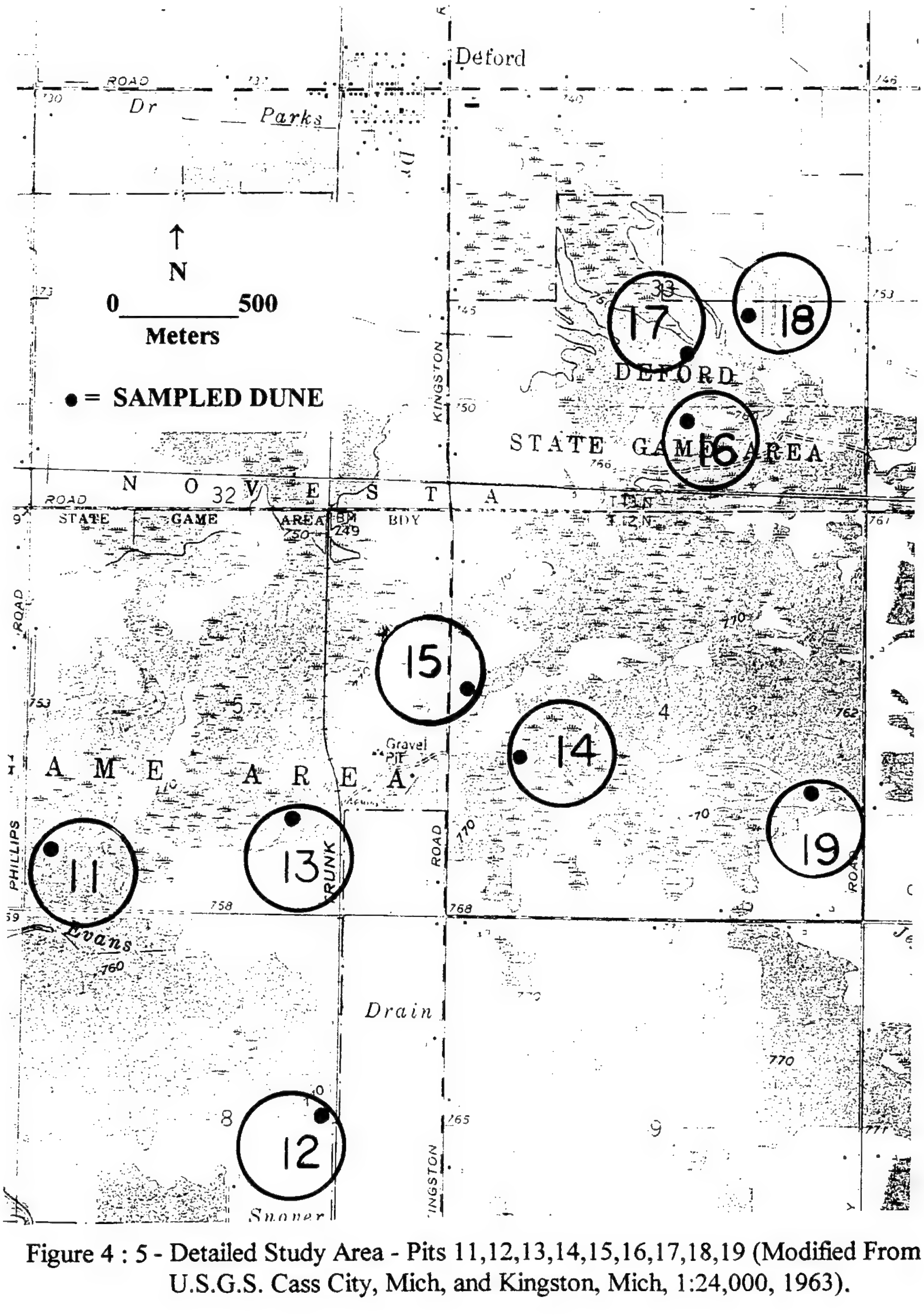


Figure 4 : 5 - Detailed Study Area - Pits 11,12,13,14,15,16,17,18,19 (Modified From U.S.G.S. Cass City, Mich, and Kingston, Mich, 1:24,000, 1963).

complexes. This extraction is gaining popularity with researchers because it is believed to capture the essence of both theories of podzolization (Schaetzl, personal comm.).

Extractions of Fe (Fe_d) and Al (Al_d) were taken for Bs and C horizons in Na citrate-bicarbonate-dithionite (CBD), and acid ammonium oxalate (Fe_o, Al_o) (Soil Conservation Service, 1990). Fe and Al concentrations of the extracts were measured on a DCP spectophotometer (Soil Conservation Service, 1990; Daly, 1982). The results of these two extractions provides an indication of the amount of iron and aluminum that have been released by weathering and exist in crystalline form in the Bs horizon of each pedon (Schaetzl, personal comm.). Horizon-weighted amounts of Fe_d, Fe_o, Al_d, and Al_o for all Bs horizons were determined by multiplying the amounts of each extract by the horizon thickness in cms. Solum-weighted amounts of each particle size separate were calculated by summing each horizon-weighted total and dividing the sum by solum thickness. Silt and clay content was determined by hydrometer method of particle size analysis (Sheldrick and Wang, 1993). Reaction of samples in 2:1 water-soil mixtures was tested using an Orion pH meter, model # 720A, equipped with an Orion probe.

Soils data were analyzed using several statistical techniques. The null hypotheses for these analyses was that no significant differences existed in the data between dune soils in the and the other Saginaw lowland dune fields (Arbogast et al., in press). Raw data input into these analyses included POD Indices, B horizon and solum thickness's, pH data for A, E, Bs, BC, and C horizons, textural class data for each horizon, and Fe_d, Fe_o, Al_d, and Al_o contents for Bs and C horizons. Principal components analysis was performed to identify if associations that explain the variation within the data set existed, and cluster analysis was performed to identify groupings of similar dunes. Analysis of variance (ANOVA) and

Kruskal-Wallis (K-W) tests were performed to determine whether statistically significant differences existed, at $\alpha = 0.05$, for each of the variables listed above.

To assess whether the dunes in the Tuscola County dune field have been stable for approximately the same length of time as the other Saginaw dune fields (Gratiot, Midland, and Arenac Counties) the descriptive variables generated for each dune pedon through field observation and laboratory analysis were analyzed statistically through principal components analysis (PCA). PCA is used to study the correlations (degree of a relationship) of a large number of variables by grouping the variables in "factors" such that the variables within each factor are highly correlated (Rummel,1967). PCA aids in classification by revealing the structural elements, and reducing the number of redundant variables in the data set. The factors resulting from PCA are thus a summary of many variables and can be interpreted according to the variables that make up each specific factor.

PCA requires a number of user decisions, including the choice of which variables to include or exclude from the analysis, the specific matrix to factor, the number of components to limit the analysis to, and the choice of method to rotate the loadings (Wilkinson, 1992). In this PCA, all dunes sampled in the four counties (Tuscola, Gratiot, Midland, Arenac) were included.

The choice of matrix for the analysis is limited to correlation or covariance. Most often PCA is applied to a matrix of correlation coefficients among all the variables (Rummel, 1967). A correlation matrix is also the preferred choice when comparing

variables that possess different units of measurement, as is the case with this analysis. Therefore, a correlation matrix was selected.

The selection of the number of components was the most complex portion of the analysis. The number of components is the number of substantively meaningful independent (uncorrelated) patterns of relationship among the variables that can be identified (Rummel, 1967). To determine the meaningful patterns of relationship, three rules were applied. Components were limited to those with eigenvalues of ≥1.00. Eigenvalues are the sum of squared component loadings (degree and direction of relationship of the variables). Secondly, components were limited to those that explained at least 5% of the variation within the variables. Lastly, components were limited to those that contained at least one loading of ≥0.50. Loadings can range from +1.00 to - 1.00.

The final user defined choice in this PCA involved the choice of rotation. In an unrotated components matrix, component patterns are ordered by the amount of data variation they account for and define the general patterns of relationship. Rotated matrices aid in the interpretation of the components because they make the variable loadings for each component large or small; this helps to delineate the distinct groupings of relationships, if they exist (Rummel, 1967). Three types of rotation are commonly applied to component matrices: quartimax, varimax, and equamax. Varimax is the most commonly used (Johnston, 1978), and thus, was used in this PCA. The strength of Varimax is its ability to discern the same cluster of variables regardless of the number of other variable combinations in the analysis (Rummel, 1967).

PCA yields two useful matrices, the components matrix, and the factor-score matrix. As has been stated, the components matrix is used to identify the number of meaningful independent patterns of relationships among the variables. Once the number of patterns or factors has been identified, the researcher studies the loadings and attempts to attach an appropriate label to the underlying influences causing the patterns (Rummel, 1967). The factor-score matrix contains a score for each case (i.e., each dune) on each pattern or factor. The factor scores are derived by proportionally weighting each variable to its involvement in a pattern; the more involved, the higher the weight. Plotting the factor scores on a map of the cases helps to confirm the influences causing the patterns and may identify patterns in the data set (Johnston, 1978).

Finally, in order to assess the dominant wind direction at the time of dune formation, a "sand-rose" diagram was constructed for the Tuscola County dune field. A sand rose is a circular histogram which represents potential sand drift from the 16 directions of the compass, and is a graphical representation of both the amount of potential sand drift and it's directional variability (Fryberger, 1975). Following the procedure described by Arbogast et al., (in Press), the azimuth of the axis of all identifiable dunes within an eight kilometer radius around the centriod of the Tuscola dune field was determined, the readings were summed, and a sand rose diagram calculated. This diagram was compared to sand roses for the other Saginaw lowland dune fields and a wind-rose diagram constructed for Flint, Michigan.

CHAPTER V

RESULTS AND DISCUSSION

In order to attribute morphological and chemical differences between soils solely to differences in age, the remaining soil forming factors (climate, organisms, relief, and parent material) must be constant. The same is true, if soils are used, when attempting to determine the relative age of two or more dune fields. For any comparison of dune field age (based on soils data) to be valid, the four soil forming factors other than time must not differ. The design of this study, has sought to ensure that differences between the soils in these dune fields could be explained only by the factor of time.

The soil forming factors of climate, organisms, and relief between dunes in the study area, and between the other Saginaw Lowland dune fields, were compared qualitatively and do not directly enter into the following statistical analysis of soils. All four dune fields lie on the lake plain of the former glacial Lake Saginaw, are within 100 km of each other, and have no major physiographic boundaries between them. Climatically, these four dune fields are similar, with only the Arenac dune field, the most northerly, having a climate that is possibly different enough so as to be more favorable to podzolization.

Differences in organisms, limited to vegetation in both studies, are not apparent. The investigation of the pre-settlement history of the region determined that both the Cass River Valley (Tuscola County), and the Tittabawassee River Valley (Midland and Arenac Counties) were both dominated by extensive stands of *Pinus strobus* on the drier soils

(Mills, 1918). Although the vegetative history of Gratiot County was not specifically investigated in this study, Arbogast et al. (in press) concluded that the sand dunes across their entire study area (Gratiot, Midland, and Arenac Counties) were probably vegetated by a combination of *Pinus* and *Quercus* because the dune soils are droughty and excessively drained.

Dune soils in Gratiot County are mapped as mixed, mesic, Typic Udipsamments, while sandy, mixed, mesic, Entic Haplorthods and mixed, frigid, Entic Haplorthods are mapped on dunes in Midland and Arenac respectively (Arbogast et al., in press). Tuscola dune soils are mapped as mixed, mesic, Alfic Udipsamments, and sandy, mixed, mesic, Entic Haplaquods. Although Entic Haplaquods are poorly drained, a cross check with the county soil survey confirmed that no poorly drained soils were included in the data presented for Tuscola County. Therefore, all dune soils examined in both studies are thought to be well drained or better. In both studies, soil samples were obtained exclusively from dune crests. This uniform sampling method helped to ensure that uniformity in drainage was maintained. Lastly, the slope of all dunes, included in both studies, was determined by comparing rise over run on the topographic map sheets. A mean slope was then determined for each dune field. Mean slopes ranged from a high of 15 % in Arenac, to a low of 5.6 % in Midland, with Gratiot and Tuscola dunes possessing mean slopes of 7.4 % and 10 % respectively.

Soils: General

Morphologically, the soils are similar within the Tuscola County dune field (Table 5:1) consisting of A-E-Bs-BC-C horizonation. The modal Munsell colors for each horizon are:

Table 5 :1 - Raw Data, Tuscola County Dunes

Profile	Horizon	Depth(cm)	Color	pH	Texture	vcs	cs	ms	fs	vfs	sand	silt	clay	%Al (clt)	%Fe (clt)	%Al (ox)	%Fe (ox)
T1	A	0-1	10YR2/2	5.26	sand	0.5	16.3	61.1	15.0	0.5	93.4	6.6	0.0				
T1	E	1-3	10YR3/2	4.77	sand	0.2	11.0	63.3	21.3	0.8	96.6	3.4	0.0				
T1	Bw	3-21	10YR5/4	4.97	sand	0.2	13.1	63.3	20.9	0.5	98.0	2.0	0.0	0.04	0.17	0.07	0.06
T1	C	21-47	10YR4/3	4.86	sand	0.4	8.1	59.5	27.3	1.2	96.5	3.5	0.0	0.07	0.26	0.08	0.09
T1	2Ab	47-70	10YR3/3	4.82	sand	0.5	7.0	57.9	26.7	1.5	93.6	6.4	0.0	0.08	0.29	0.10	0.14
T1	2Bsb1	70-90	10YR4/4	4.91	sand	0.5	9.7	63.5	21.4	0.8	95.9	4.1	0.0	0.07	0.21	0.13	0.10
T1	2Bsb2	90-114	10YR5/6	5.21	sand	1.2	13.5	64.7	17.8	0.2	97.4	2.6	0.0	0.06	0.21	0.11	0.09
T1	2BCb	114-145	10YR5/6	6.13	sand	0.6	9.2	65.9	22.2	0.5	98.4	1.6	0.0	0.04	0.18	0.10	0.06
T1	2Cb	145-153	10YR5/6	6.31	sand	1.2	14.6	68.4	13.5	0.1	97.8	2.2	0.0	0.03	0.23	0.05	0.07
T2	A	0-2	10YR4/3	5.16	sand	0.0	5.5	61.4	26.9	1.1	94.9	5.1	0.0				
T2	C	2-26	10YR3/4	5.36	sand	0.3	5.3	58.5	32.1	1.7	97.9	2.1	0.0	0.06	0.27	0.08	0.09
T2	2Ab	26-54	10YR3/4	5.70	sand	0.3	11.6	62.7	19.6	0.8	95.0	5.0	0.0	0.07	0.30	0.10	0.14
T2	2Bsb	54-78	10YR4/4	6.03	sand	0.2	9.3	62.7	23.4	0.9	96.5	3.5	0.0	0.06	0.26	0.10	0.10
T2	2BCb	78-114	10YR4/6	6.15	sand	0.2	13.7	63.6	20.3	0.8	98.6	1.4	0.0	0.03	0.19	0.06	0.06
T2	2Cb	114-135	10YR4/4	6.22	sand	1.1	19.3	60.7	16.8	0.3	98.2	1.8	0.0	0.02	0.17	0.03	0.04
T3	A	0-12	10YR3/3	5.92	sand	0.1	8.2	56.0	25.6	2.3	92.2	7.8	0.0				
T3	Bs	12-49	7.5YR4/4	6.00	sand	0.3	13.9	65.6	15.4	0.5	95.7	4.3	0.0	0.12	0.32	0.21	0.16
T3	BC	49-89	10YR4/6	6.25	sand	0.3	13.8	65.5	18.3	0.7	98.5	1.5	0.0				
T3	C	89-109	10YR5/6	6.32	sand	0.1	13.0	62.9	20.9	1.0	97.9	2.1	0.0	0.03	0.14	0.06	0.04
T4	A	0-7	10YR3/1	4.73	sand	0.1	7.3	66.3	18.1	1.7	93.5	6.5	0.0				
T4	Bs	7-55	10YR4/6	5.98	sand	0.1	6.9	68.9	18.8	0.9	95.6	4.4	0.0	0.09	0.33	0.13	0.10
T4	BC	55-106	10YR5/6	7.34	sand	0.2	10.2	65.6	19.7	1.3	97.0	3.0	0.0				
T4	C	106-135	10YR5/4	8.52	sand	0.0	0.8	63.6	31.5	2.4	98.3	1.7	0.0	0.05	0.13	0.09	0.04
T5	A	0-12	10YR2/1	4.15	sand	0.2	4.9	67.6	18.2	1.0	91.9	8.1	0.0				
T5	E	12-21	10YR4/2	4.61	sand	0.1	2.9	65.9	25.1	2.1	96.1	3.9	0.0				
T5	Bs	21-81	7.5YR4/6	5.85	sand	0.1	4.0	71.1	20.2	0.4	95.8	4.2	0.0	0.12	0.40	0.24	0.16
T5	BC	81-116	10YR5/6	6.37	sand	0.1	3.3	70.8	24.3	0.6	99.1	0.9	0.0				
T5	C	116-125	10YR4/4	6.31	sand	0.0	1.4	74.9	22.1	0.6	99.0	1.0	0.0	0.03	0.11	0.06	0.03
T6	A	0-12	10YR3/1	4.24	sand	0.0	3.1	63.0	26.5	1.6	94.2	5.8	0.0				
T6	E	12-27	10YR5/2	4.76	sand	0.2	3.2	64.9	26.6	1.7	96.6	3.4	0.0				

Table 5 :1 - Raw Data, Tuscola County Dunes

T6	Bs	27-65	7.5YR4/6	5.62	sand	0.1	2.7	66.1	27.4	0.7	97.0	3.0	0.0	0.23	0.47	0.38	0.21
T6	BC	65-112	10YR5/6	6.27	fine sd	0.0	0.3	37.8	57.6	3.7	99.4	0.6	0.0				
T6	C	112-134	10YR5/4	6.43	sand	0.0	0.7	76.7	21.5	0.2	99.1	0.9	0.0	0.02	0.14	0.04	0.05
T7	A	0-8	10YR3/1	4.74	sand	0.2	6.3	55.8	28.5	2.6	93.4	6.6	0.0				
T7	E	8-16	10YR4/2	4.65	sand	0.3	9.5	61.8	22.0	1.6	95.2	4.8	0.0				
T7	BS	16-63	10YR4/6	5.13	sand	0.3	9.4	60.1	23.9	1.1	94.8	5.2	0.0	0.13	0.47	0.20	0.15
T7	BC	63-121	10YR5/8	6.22	sand	0.1	7.5	63.7	25.9	1.3	98.5	1.5	0.0				
T7	C	121-129	10YR5/6	6.30	sand	0.1	9.7	64.3	22.3	1.0	97.4	2.6	0.0	0.04	0.22	0.05	0.07
T8	A	0-13	10YR2/1	5.34	sand	0.1	2.3	61.4	29.1	1.0	93.9	6.1	0.0				
T8	Bs	13-51	10YR4/6	5.84	sand	0.0	1.3	56.1	36.9	1.3	95.6	4.4	0.0	0.07	0.28	0.11	0.11
T8	BC	51-83	10YR5/6	6.59	sand	0.0	1.0	57.3	40.3	1.0	99.6	0.4	0.0				
T8	C	83-116	10YR5/6	6.01	sand	0.0	0.7	56.9	39.8	1.3	98.7	1.3	0.0	0.03	0.13	0.06	0.05
T9	A	0-13	10YR3/3	5.18	sand	0.0	2.3	54.0	36.6	1.5	94.4	5.6	0.0				
T9	Bs	13-60	7.5YR4/6	5.44	sand	0.0	2.3	61.1	33.5	0.4	97.3	2.7	0.0	0.13	0.31	0.44	0.18
T9	BC	60-85	10YR5/6	5.81	sand	0.1	2.7	69.8	26.4	0.2	99.2	0.8	0.0				
T9	C	85-108	10YR5/6	6.19	sand	0.1	2.3	57.7	38.2	0.7	99.0	1.0	0.0	0.04	0.13	0.09	0.04
T10	A	0-8	10YR3/1	4.81	sand	0.0	1.5	49.5	40.4	2.1	93.5	6.5	0.0				
T10	E	8-19	10YR5/3	5.00	sand	0.0	1.3	53.5	39.5	1.7	96.0	4.0	0.0				
T10	Bs	19-79	7.5YR4/6	5.61	sand	0.0	1.1	49.5	45.5	1.7	97.8	2.2	0.0	0.18	0.44	0.35	0.28
T10	BC	79-110	10YR4/6	6.00	sand	0.1	3.5	58.9	36.6	0.9	100.0	0.0	0.0				
T10	C	110-128	10YR5/6	6.10	fine sd	0.0	1.1	47.2	49.3	1.7	99.3	0.7	0.0	0.04	0.13	0.08	0.05
T11	A	0-7	10YR2/1	4.56	fine sd	0.0	0.9	36.7	50.1	3.4	91.1	8.9	0.0				
T11	E	7-17	10YR4/2	4.80	fine sd	0.0	0.7	41.5	50.4	3.3	95.9	4.1	0.0				
T11	Bs	17-50	7.5YR4/6	5.66	fine sd	0.0	0.4	36.5	57.0	3.1	97.0	3.0	0.0	0.19	0.43	0.57	0.28
T11	BC	50-82	10YR4/6	5.94	fine sd	0.0	0.3	43.7	53.5	1.7	99.2	0.8	0.0				
T11	C	82-95	10YR4/4	6.35	sand	0.0	0.1	55.5	42.6	1.1	99.3	0.7	0.0	0.05	0.10	0.11	0.04
T12	A	0-6	10YR2/1	4.58	sand	0.0	2.2	43.8	42.0	2.4	90.4	9.6	0.0				
T12	E	6-28	10YR5/2	4.62	sand	0.0	2.2	50.7	43.0	1.3	97.2	2.8	0.0				
T12	Bs	28-68	7.5YR4/6	5.30	fine sd	0.0	1.7	45.9	49.3	0.8	97.7	2.3	0.0	0.19	0.40	0.55	0.22
T12	BC	68-102	10YR5/6	5.84	sand	0.1	2.1	59.9	35.7	0.9	98.7	1.3	0.0				

Table 5 :1 - Raw Data, Tuscola County Dunes

T12	C	102-121	10YR5/4	5.91	sand	0.0	2.7	48.5	45.7	2.3	99.2	0.8	0.0	0.05	0.13	0.12	0.05
T13	A	0-9	10YR3/1	4.37	sand	0.3	4.6	56.3	30.9	1.9	94.0	6.0	0.0				
T13	E	9-24	10YR4/2	4.97	sand	0.0	3.2	60.4	30.7	2.1	96.4	3.6	0.0				
T13	Bs	24-70	7.5YR4/6	5.75	sand	0.0	4.1	65.5	26.6	1.1	97.3	2.7	0.0	0.15	0.35	0.51	0.18
T13	BC	70-103	10YR5/4	6.33	sand	0.1	4.8	63.6	28.8	1.7	99.0	1.0	0.0				
T13	C	103-128	10YR5/4	6.61	sand	0.0	3.3	61.8	33.0	0.7	98.8	1.2	0.0	0.04	0.13	0.07	0.04
T14	A	0-13	10YR3/2	4.46	sand	0.2	4.8	55.1	33.1	2.2	95.4	4.6	0.0				
T14	E	13-22	10YR5/2	4.77	sand	0.1	2.9	54.9	36.6	2.3	96.8	3.2	0.0				
T14	Bs	22-65	7.5YR4/6	5.24	sand	0.2	2.8	56.6	37.0	1.7	98.3	1.7	0.0	0.13	0.29	0.35	0.17
T14	BC	65-94	10YR5/6	5.64	sand	0.1	3.7	59.9	33.9	0.9	98.5	1.5	0.0				
T14	C	94-112	10YR4/4	5.87	sand	0.0	4.7	60.9	32.3	1.3	99.2	0.8	0.0	0.05	0.11	0.13	0.05
T15	A	0-11	10YR2/1	5.60	fine sd	0.0	0.4	37.3	50.6	3.7	92.0	8.0	0.0				
T15	Bs	11-47	7.5YR4/6	5.89	fine sd	0.0	0.5	44.4	49.3	2.5	96.7	3.3	0.0	0.10	0.26	0.22	0.11
T15	BC	47-75	10YR5/6	6.18	sand	0.1	4.3	50.1	43.3	1.5	99.3	0.7	0.0				
T15	C	75-118	10YR5/4	6.11	fine sd	0.0	0.7	47.9	48.7	2.5	99.8	0.2	0.0	0.03	0.11	0.07	0.03
T16	A	0-12	10YR2/1	4.38	sand	0.0	1.8	56.5	33.0	2.3	93.6	6.4	0.0				
T16	Bs	12-56	7.5YR4/6	5.19	sand	0.0	1.4	58.1	35.3	1.7	96.5	3.5	0.0	0.16	0.36	0.30	0.15
T16	BC	56-98	10YR5/6	5.74	sand	0.0	2.3	65.4	30.4	0.7	98.8	1.2	0.0				
T16	C	98-132	10YR5/6	6.04	sand	0.0	2.8	64.9	30.9	0.6	99.2	0.8	0.0	0.03	0.17	0.04	0.04
T17	A	0-12	10YR3/1	4.79	sand	0.0	2.3	61.8	30.9	1.1	96.1	3.9	0.0				
T17	Bs	12-59	7.5YR4/6	5.58	sand	0.0	1.7	58.1	37.2	1.0	98.0	2.0	0.0	0.13	0.30	0.41	0.19
T17	BC	59-114	10YR5/6	6.15	sand	0.0	1.9	59.7	35.7	1.1	98.4	1.6	0.0				
T17	C	114-147	10YR5/6	6.24	sand	0.1	3.0	65.5	30.3	0.7	99.6	0.4	0.0	0.03	0.12	0.07	0.03
T18	A	0-9	10YR3/1	4.78	sand	0.0	2.9	55.8	35.2	1.9	95.8	4.2	0.0				
T18	E	9-21	10YR5/2	5.01	sand	0.1	2.1	53.9	38.9	1.7	96.7	3.3	0.0				
T18	Bs	21-57	7.5YR4/6	5.15	sand	0.1	2.7	61.0	32.9	0.5	97.2	2.8	0.0	0.16	0.35	0.44	0.20
T18	BC	57-87	10YR5/6	5.76	sand	0.0	1.9	56.1	40.5	0.7	99.2	0.8	0.0				
T18	C	87-125	10YR5/6	6.06	sand	0.0	1.9	62.7	34.0	0.5	99.1	0.9	0.0	0.04	0.10	0.09	0.04

Table 5 :1 - Raw Data, Tuscola County Dunes

T19	A	0-9	10YR2/1	4.39	sand	0.0	2.9	46.5	41.9	1.9	93.2	6.8	0.0				
T19	E	9-24	10YR4/2	4.78	fine sd	0.0	0.6	46.0	47.8	2.5	96.9	3.1	0.0				
T19	Bs	24-66	7.5YR4/6	5.80	fine sd	0.0	0.4	37.4	57.5	1.7	97.0	3.0	0.0	0.18	0.40	0.54	0.22
T19	BC	66-105	10YR5/6	6.09	fine sd	0.0	0.3	40.6	57.3	1.3	99.5	0.5	0.0				
T19	C	105-134	10YR5/6	5.84	sand	0.0	0.1	51.4	46.5	0.9	98.9	1.1	0.0	0.03	0.10	0.07	0.04

A (10YR 2/1 and 3/1), E (10YR 4/2), Bs (7.5 YR 4/6), BC (10YR 5/6), C (10YR 5/6). Textural class data of the C horizons supports the notion of parent material uniformity, with most textures classifing as "sand" (> 97% sand, <2% silt, 0% clay).

In comparison, the mean horizon sequence of the other Saginaw dune fields was consistent, although about half of the soils lacked an E horizon, and some had E/B horizons instead of an E. Horizon colors are slightly different, with Tuscola A and E horizons grayer in chroma and C horizons darker in value (Figure 5:1). Parent material is generally consistent, with Tuscola soils containing slightly more silt than the others.

Soils: Statistical Analysis

ANOVA and K-W tests were performed on each of the morphological and chemical variables. ANOVA involves the partitioning of a data set into three or more subsets (in this case dune fields), for the purpose of testing a hypothesis that the means of the populations of the subsets are equal. ANOVA tests this hypothesis by breaking down the total variance of the data set into its component sources of variance. The prerequisites for ANOVA are that the populations, in this case dune fields, are normally distributed and have homogeneous variances. In the ANOVA test there are two components of variance. The first is the variance within each population (dune field). The second is the variance between each of the populations. Greater variation between the dune fields than within the dune fields suggests that the dune fields being compared are significantly different. The small sample sizes used in this study (10 dunes in each of Gratiot, Midland, and Arenac Counties and 19 dunes in Tuscola County) create some doubt as to whether the

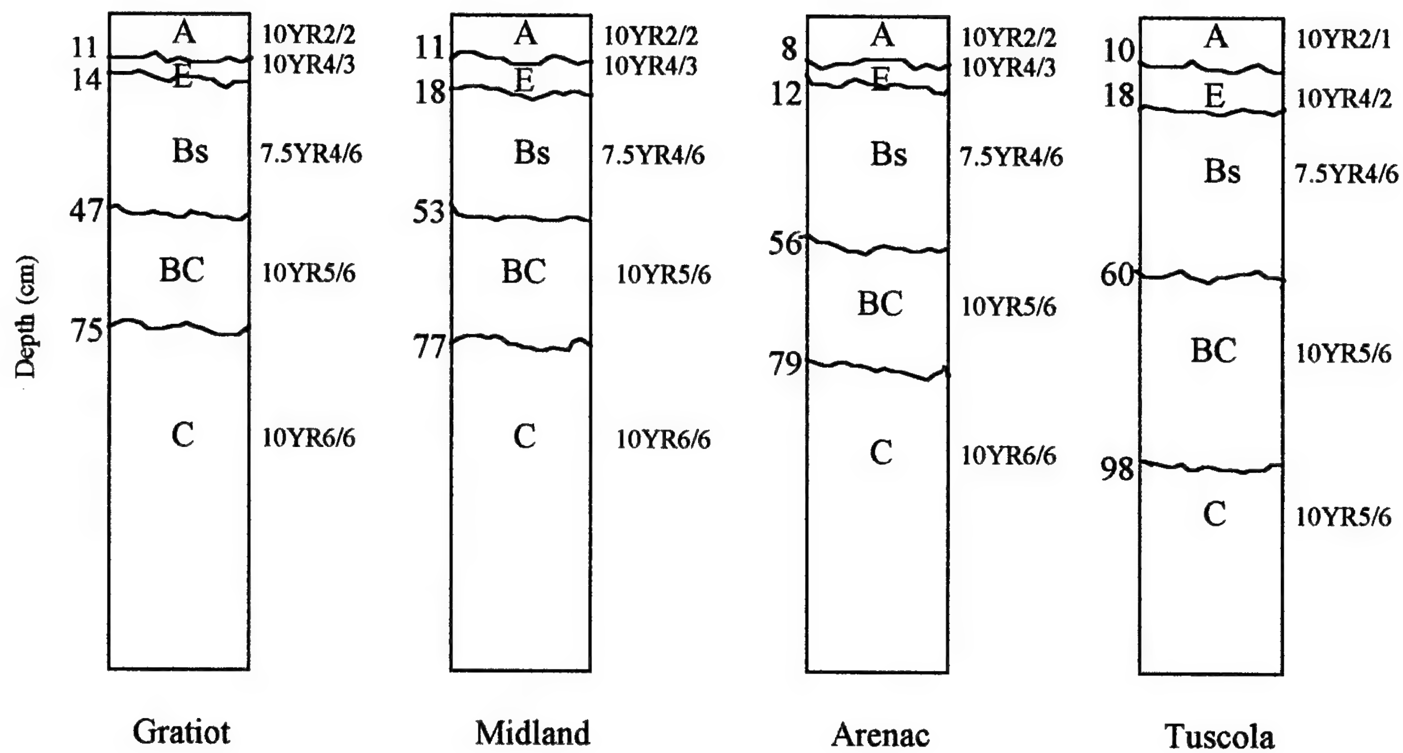


Figure 5 : 1 - Generalized soil morphology of Saginaw Lowland dune fields

prerequisite of normalcy has been satisfied. Therefore, in this study the results of ANOVA were compared to the results of K-W tests, which is the non-parametric equivalent of the parametric ANOVA test. The K-W test involves combining the values for the subsets and then ranking them, employing a null hypothesis that there is no significant difference in the ranks of the subsets (Earickson and Harlan, 1994). When employing two significance tests to answer a single question, conflicting results are bound to occur. In this study, the following standards for resolving such conflicts were used: when the results of the two tests differed, the result of the more conservative K-W test presided.

The null hypotheses for these tests were that no differences existed in the data for the Tuscola soils compared to the other Saginaw dune field soils (T vs. G+M+T). Significant differences existed with respect to B horizon and solum thickness, and all but two of the B and C horizon Fe and Al contents (Table 5:2). These differences indicate a greater degree of soil development in the Tuscola soils. Tuscola soils are significantly thicker overall, with significantly thicker B horizons. Tuscola B horizons exhibit significantly more translocation of Fe and Al. Tuscola B horizons exhibit 120% more translocation of Fe based on Fe_dwt, 95% more translocation of Fe based on Fe_owt, and 88% more translocation of Al based on Al_owt.

The second group of significant differences between the soils are related more to inherited (parent material), rather than developmental (horizon and solum characteristics) characteristics. Significant differences exist in very coarse sand, medium sand, very fine sand, total sand, and total silt fraction amounts for the C horizons of the soils between the

Table 5 : 2 - Significance Testing of Morphological and Chemical Data

VARIABLE		ANOVA	Kruskal-Wallis			
	Tuscola	Sig. Diff.?	Sig. Diff.?	Gratiot	Midland	Arenac
POD Index	0.56 (0.9)	NO	NO	0.00 (0.0)	0.40 (0.8)	0.40 (0.8)
B thickness(cm)	42.1 (9.0)	YES	YES	32.9 (4.8)	35.0 (8.1)	41.6 (8.9)
Solum thickness (cm)	98.3 (13.1)	YES	YES	75.0 (7.7)	76.6 (11.5)	79.2 (12.9)
A Horizon pH	4.8 (0.5)	YES	YES	4.4 (0.3)	4.2 (0.3)	4.6 (0.5)
E Horizon pH	4.8 (0.2)	YES	YES	4.9 (0.1)	4.5 (0.0)	4.5 (0.3)
Bs Horizon pH	5.6 (0.3)	YES	YES	5.5 (0.3)	5.4 (0.3)	5.3 (0.4)
BC Horizon pH	6.2 (0.4)	YES	YES	5.9 (0.3)	5.8 (0.3)	5.6 (0.5)
C Horizon pH	6.3 (0.6)	YES	NO	6.2 (0.3)	6.0 (0.4)	5.9 (0.3)
VCS %	0.1 (0.4)	NO	YES	0.5 (0.6)	0.3 (0.5)	0.1 (0.2)
CS %	4.4 (5.6)	NO	NO	9.4 (4.5)	7.2 (5.2)	1.2 (1.6)
MS %	60.7 (8.2)	YES	YES	57.8 (4.4)	59.3 (5.8)	42.7 (11.3)
FS %	32.6 (11.0)	NO	NO	30.0 (5.1)	31.0 (8.9)	50.1 (10.5)
VFS %	1.1 (0.7)	YES	YES	1.5 (1.3)	1.5 (1.0)	5.3 (2.8)
Sand %	98.8 (0.6)	YES	YES	99.2 (0.3)	99.2 (0.7)	99.4 (0.5)
Silt %	1.2 (0.6)	YES	YES	0.9 (0.4)	0.8 (0.7)	0.6 (0.5)
Clay %	0.0 (0.0)	NO	NO	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Bs Horizon Ald %	0.15 (0.04)	NO	NO	0.15 (0.02)	0.14 (0.06)	0.13 (0.03)
Bs Horizon Alo %	0.35 (0.15)	YES	YES	0.23 (0.05)	0.24 (0.07)	0.22 (0.06)
Bs Horizon Fed %	0.36 (0.07)	YES	YES	0.20 (0.05)	0.19 (0.06)	0.19 (0.03)
Bs Horizon Feo %	0.18 (0.05)	YES	YES	0.12 (0.02)	0.10 (0.03)	0.11 (0.02)
C Horizon Ald %	0.03 (0.01)	YES	NO	0.05 (0.01)	0.04 (0.01)	0.04 (0.01)
C Horizon Alo %	0.07 (0.03)	YES	YES	0.06 (0.02)	0.05 (0.02)	0.05 (0.01)
C Horizon Fed %	0.14 (0.04)	YES	YES	0.10 (0.02)	0.07 (0.01)	0.09 (0.02)
C Horizon Feo %	0.04 (0.01)	YES	YES	0.02 (0.00)	0.02 (0.01)	0.02 (0.01)
Bs Horizon Fed Weighted	15.5 (4.9)	YES	YES	6.7 (1.7)	6.3 (2.0)	7.8 (1.9)
Bs Horizon Alo Weighted	14.4 (5.9)	YES	YES	7.7 (2.1)	7.8 (1.8)	9.1 (3.0)
Bs Horizon Feo Weighted	7.6 (3.0)	YES	YES	4.1 (1.1)	3.5 (0.8)	4.5 (1.2)

two groups (Table 5:2). The mean amount of medium sand in the C horizon, in the Tuscola soils, is more than the Saginaw group (60.7 vs. 57.8, 59.3, and 42.7 %, respectively). Tuscola soils have more silt in the parent material than the Saginaw group, but this difference is extremely small (1.2 vs. 0.9, 0.8, and 0.6 %, respectively). As a result of this difference in silt, the total sand percentage is slightly less in Tuscola parent materials (98.8 vs. 99.3, 99.2, and 99.4%, respectively). The mean amount of very coarse sand is also slightly less in Tuscola parent materials, but again this difference is also extremely small (0.1 vs. 0.5, 0.3, and 0.1% respectively).

The mean pH values were significantly different between the two groups for A, E, Bs, and BC horizons. These horizons are significantly more alkaline in Tuscola soils (Table 5:2). At this time this difference cannot be adequately explained. It is possible that Tuscola dunes are formed from an alluvium that is different from the other Saginaw Lowland dune fields. Based on dune orientation Tuscola dunes lay downwind of the Saginaw lake plain, an area of calcareous soils (Schaetzl, personal comm.) and as a result, the Tuscola soils could possibly have inherited calcareous sediment from the lake plain. Toward that end, Tuscola parent materials have significantly more silt. The second source of alluvium for Tuscola soils could be from glacial Lake Whittlesey, which drained westward across Michigan through the Tuscola study area prior to dune formation.

Of the 27 variables, some being redundant, that were compared between the Tuscola dunes and the other Saginaw dunes, only six did not exhibit significant differences. Significant differences in parent materials do not exist for coarse sand, fine sand, total clay (no dune soils in either study possessed any measurable clay), and C horizon pH. The only developmental variable that failed to show a significant difference between Tuscola

and the other Saginaw dune fields was the POD index. The mean POD index for Tuscola soils was 0.56, while soils in the other dune fields had POD indices of 0.00, 0.40, and 0.40 respectively (with POD index limits of 0-2 being indicative of non-Spodosols, the validity of comparing such relatively weakly developed soils using this index is questionable). Nonetheless, the index appears to indicate that Tuscola soils are more developed than the other dune field soils.

Principal Components Analysis

Variables included in the PCA are listed in Table 5:3. Variables excluded were E horizon pH, medium sand, total sand, and non-weighted Fe and Al extraction data. E horizon pH was not included because several dunes did not contain E horizons. Medium sand, total sand, and unweighted (mass-based) B horizon extraction data were excluded to avoid problems with colinearity. Colinearity results when two variables are perfectly correlated. Medium sand, the dominant separate fraction, was excluded because the particle size separates sum to 100%, while total sand, averaging 99% across the dune fields, is too close to 100% to avoid colinearity (Winkler, personal comm.). Unweighted (mass-based) B horizon extraction data were not included because the weighted (volume-based) B horizon extraction data, the preferable means of reporting soils data, was included (Schaetzl, personal comm.). Finally, C horizon extraction data were excluded because there is no precedence for its use as a relative age dating tool in the literature.

Table 5 : 3 - Principal Components Analysis - Raw Data

Profile	Bs Thick	SOL Thick	ApH	BpH	BCpH	CpH	vcs	cs	fs	vfs	silt	BFedwt	BAlowt	BFeowt
T3	37	89	5.92	6.00	6.25	6.32	0.1	13.0	20.9	1.0	2.1	11.84	7.77	5.92
T4	48	106	4.73	5.98	7.34	8.52	0.0	0.8	31.5	2.4	1.7	15.84	6.24	4.80
T5	60	116	4.15	5.85	6.37	6.31	0.0	1.4	22.1	0.6	1.0	24.00	14.40	9.60
T6	38	112	4.24	5.62	6.27	6.43	0.0	0.7	21.5	0.2	0.9	17.86	14.44	7.98
T7	47	121	4.74	5.13	6.22	6.30	0.1	9.7	22.3	1.0	2.6	22.09	9.40	7.05
T8	38	83	5.34	5.84	6.59	6.01	0.0	0.7	39.8	1.3	1.3	10.64	4.18	4.18
T9	47	85	5.18	5.44	5.81	6.19	0.1	2.3	38.2	0.7	1.0	14.57	20.68	8.46
T10	60	110	4.81	5.61	6.00	6.10	0.0	1.1	49.3	1.7	0.7	26.40	21.00	16.80
T11	33	82	4.56	5.66	5.94	6.35	0.0	0.1	42.6	1.1	0.7	14.19	18.81	9.24
T12	40	102	4.58	5.30	5.84	5.91	0.0	2.7	45.7	2.3	0.8	16.00	22.00	8.80
T13	46	103	4.37	5.75	6.33	6.61	0.0	3.3	33.0	0.7	1.2	16.10	23.46	8.28
T14	43	94	4.46	5.24	5.64	5.87	0.0	4.7	32.3	1.3	0.8	12.47	15.05	7.31
T15	36	75	5.60	5.89	6.18	6.11	0.0	0.7	48.7	2.5	0.2	9.36	7.92	3.96
T16	44	98	4.38	5.19	5.74	6.04	0.0	2.8	30.9	0.6	0.8	15.84	13.20	6.60
T17	47	114	4.79	5.58	6.15	6.24	0.1	3.0	30.3	0.7	0.4	14.10	19.27	8.93
T18	36	87	4.78	5.15	5.76	6.06	0.0	1.9	34.0	0.5	0.9	12.60	15.84	7.20
T19	22	105	4.39	5.80	6.09	5.84	0.0	0.1	46.5	0.9	1.1	8.80	11.88	4.84
G1	32	74	4.20	5.42	5.91	6.37	2.0	14.2	24.5	0.7	0.8	7.04	8.64	3.84
G2	39	70	4.36	5.03	5.12	5.51	0.1	7.9	33.3	0.9	0.6	6.24	10.14	5.46
G3	28	70	4.50	6.00	6.15	6.25	0.3	11.3	23.8	0.2	1.1	7.00	7.84	4.20
G4	37	72	4.50	5.71	5.95	6.20	0.3	9.4	28.1	1.1	1.5	7.03	9.62	4.07
G5	25	68	4.03	5.26	5.89	6.06	0.5	18.7	23.3	1.0	0.5	3.00	4.50	1.75
G6	34	74	4.76	5.56	6.37	6.62	0.1	5.7	36.7	2.9	0.6	8.50	5.10	3.74
G7	27	70	4.71	6.05	6.27	6.36	0.0	3.0	30.5	0.5	0.9	5.40	5.13	2.97
G8	34	80	4.65	5.53	6.01	6.11	0.4	6.2	33.7	1.6	0.5	6.46	9.86	4.76
G9	35	78	4.11	5.21	5.81	6.17	0.5	7.3	37.0	4.5	1.0	9.45	8.40	4.90
G10	38	94	4.06	5.61	5.96	6.16	0.3	10.1	29.5	1.3	1.0	6.84	7.98	4.94
M1	33	75	3.80	5.16	5.90	6.04	0.1	7.5	33.5	3.1	0.7	6.27	5.28	2.64
M2	34	80	4.24	5.42	5.53	6.06	0.0	3.5	37.4	1.9	0.5	3.74	7.48	3.06
M3	24	67	4.19	5.93	6.44	6.63	1.5	16.7	22.3	1.3	0.7	4.32	6.24	2.40
M5	31	57	4.59	5.35	5.74	6.10	0.3	3.5	46.5	0.9	0.7	6.20	6.51	2.79
M6	31	84	4.18	5.38	5.92	6.12	0.0	4.1	31.0	0.3	0.4	6.51	11.47	4.96
M7	29	74	3.81	5.15	5.81	5.95	0.1	3.0	29.4	1.3	2.8	8.99	8.70	3.77
M9	31	65	4.09	5.76	6.02	6.00	0.0	1.7	38.9	2.2	0.4	6.20	8.06	3.72
M10	51	89	4.49	5.81	5.93	6.22	0.3	11.2	22.3	0.7	0.4	9.69	7.65	3.57
M11	42	95	4.11	4.91	5.10	5.20	0.3	14.1	16.7	0.2	0.8	4.62	8.40	4.20
A1	44	85	4.20	5.31	5.65	5.89	0.0	0.6	38.4	4.1	1.1	10.12	12.76	5.72
A2	34	79	4.20	5.30	5.31	5.93	0.1	0.9	62.1	9.2	0.5	7.82	10.88	4.76
A3	54	100	5.44	5.54	6.01	6.10	0.1	0.5	45.5	2.9	0.5	9.72	14.58	6.48
A4	50	82	4.82	5.79	6.25	6.31	0.1	0.5	61.9	4.3	0.5	8.50	8.50	4.50
A5	30	52	4.62	5.07	5.08	5.89	0.6	2.2	44.5	5.2	0.7	5.10	4.50	2.70
A6	37	66	4.61	4.87	5.38	5.52	0.1	0.7	56.5	5.4	0.4	6.29	7.03	3.70
A7	35	84	4.47	5.43	6.05	6.39	0.1	0.7	59.3	11.0	0.2	5.60	7.35	4.55
A8	34	77	4.00	4.83	4.96	5.51	0.1	5.5	31.5	3.1	1.7	6.12	6.46	3.06
A9	54	88	4.10	4.75	4.84	5.57	0.0	0.3	45.9	2.4	0.1	9.72	9.18	5.40
A10	44	79	5.20	5.62	6.00	6.01	0.0	0.2	55.3	5.5	0.6	9.24	9.68	4.40

In this PCA, five primary factors were identified among the variables (Table 5:4) which explained 82 % of the total variance. In factor 1, Fe and Al concentration in the B horizon, solum thickness, and B horizon thickness all loaded strongly positively. This is a logical relationship because as spodosols develop the concentration of Fe and Al in the B horizon, the thickness of the B horizon and the overall solum thickness increase (eg. Birkland, 1984; Franzmeier and Whiteside, 1963; Schaetzl and Mokma, 1988). Therefore, this factor which accounts for 28.4 % of the variance of the 14 variables, is interpreted as soil development.

Factor 2 had one strongly positive loading, coarse sand, opposed by two strongly negative loadings: fine and very fine sand. Thus, this factor is interpreted to reflect subtle differences in sand texture, it accounts for 17.3 % of the variance. The third pattern, centered on the pH of several soil horizons. B, BC, and C horizon pH all loaded strongly positively and were not opposed by any other variable. This factor was interpreted to be subsoil pH, and accounts for 18.5 % of the variance. Factors 4 and 5 contained only one strong loading each, and thus were easily interpreted. Silt loaded strongly negatively on factor 4, while A horizon pH loaded strongly positively on factor 5. Factors 4 and 5 accounted for 8.8 % and 9.1 % of the variance, respectively.

After the primary variables were identified by PCA, a factor scores matrix was produced (Table 5:5). The scores for each dune, relative to each factor, are displayed as standardized scores. In this analysis, factor scores ranged from + 3.87 to - 3.12. The factor scores were divided into eight groups, four positive and four negative, based on

Table 5 : 4 - Principal Components Analysis, Results

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Eigenvalue	4.455	2.958	2.178	1.028	0.884
Rotated Loadings					
B Horizon Feo Wt.	**0.935**	-0.011	0.011	0.039	0.124
B Horizon Fed Wt.	**0.888**	0.012	0.226	-0.244	0.053
B Horizon Alo Wt.	**0.851**	0.019	-0.098	0.137	0.127
Solum Thickness	**0.828**	0.077	0.196	-0.257	-0.042
B Horizon Thickness	**0.773**	-0.149	0.023	0.008	0.045
Fine Sand %	-0.014	**-0.886**	-0.107	0.271	0.181
Very Fine Sand %	-0.219	**-0.836**	-0.009	0.146	-0.25
Coarse Sand %	-0.344	**0.766**	0.03	0.122	-0.285
BC Horizon pH	0.116	0.09	**0.928**	-0.128	0.18
C Horizon pH	0.086	-0.028	**0.918**	-0.111	-0.116
B Horizon pH	0.004	0.141	**0.798**	0.105	0.422
Silt %	0.028	0.282	0.161	**-0.838**	-0.075
A Horizon pH	0.0109	-0.109	0.284	0.056	**0.797**
Very Coarse Sand %	-0.332	0.451	0.183	0.481	-0.443
% of Total Variance Explained					
	28.43%	17.29%	18.53%	8.80%	9.12%

Table 5 : 5 - Factor Scores

DUNE #	FACTOR(1)	FACTOR(2)	FACTOR(3)	FACTOR(4)	FACTOR(5)
T3	-0.50	1.43	0.74	-1.30	2.30
T4	0.26	-1.02	3.87	-1.80	-1.20
T5	2.15	0.38	0.78	-0.41	-0.73
T6	1.20	0.45	0.53	-0.58	-0.39
T7	1.06	0.78	0.24	-2.80	-0.83
T8	-0.71	-0.19	0.66	-0.95	1.98
T9	1.13	0.29	-0.35	0.40	1.20
T10	3.15	-0.31	0.03	1.02	0.21
T11	0.82	-0.17	0.08	0.48	0.61
T12	1.44	-0.26	-0.55	0.36	0.09
T13	1.57	0.29	0.71	-0.08	-0.21
T14	0.82	0.31	-0.82	-0.02	0.05
T15	-0.66	-0.58	0.45	0.85	2.45
T16	0.91	0.23	-0.59	-0.36	-0.21
T17	1.60	0.48	0.19	0.86	0.39
T18	0.56	0.25	-0.72	-0.23	0.66
T19	-0.22	-0.22	0.02	-0.65	0.74
G1	-0.47	1.87	0.83	2.32	-2.12
G2	-0.21	0.60	-1.77	0.31	0.28
G3	-0.93	1.28	0.58	0.02	0.67
G4	-0.63	0.81	0.19	-0.48	0.23
G5	-1.37	1.45	-0.20	0.62	-0.84
G6	-0.80	-0.35	0.92	0.02	0.24
G7	-1.29	0.31	0.74	-0.43	1.42
G8	-0.38	0.41	0.10	0.79	0.32
G9	-0.30	-0.33	0.04	0.04	-1.50
G10	-0.16	0.67	0.20	-0.08	-0.75
M1	-0.81	-0.22	-0.28	-0.39	-1.21
M2	-0.71	-0.22	-0.53	0.01	0.07
M3	-1.27	1.75	1.71	1.91	-1.37
M5	-1.12	-0.16	-0.34	0.25	0.64
M6	-0.17	0.37	-0.34	0.20	0.10
M7	-0.77	0.10	-0.61	-3.12	-0.95
M9	-0.81	-0.37	0.06	0.30	0.31
M10	0.06	1.06	0.37	0.81	0.01
M11	-0.05	1.69	-2.03	-0.02	-0.54
A1	0.30	-0.77	-0.55	-0.55	-0.57
A2	-0.31	-2.40	-0.39	0.50	-1.22
A3	0.76	-0.55	0.07	0.81	1.31
A4	-0.12	-1.55	0.83	0.72	0.47
A5	-1.34	-0.87	-0.88	0.44	-0.30
A6	-0.70	-1.52	-1.31	0.32	0.06
A7	-0.57	-2.85	0.88	0.72	-1.33
A8	-0.75	-0.08	-1.81	-1.72	-0.91
A9	0.65	-0.81	-1.96	0.48	-0.72
A10	-0.29	-1.47	0.21	0.39	1.07

their deviation from zero. The scores were then plotted on a schematic map of the distribution of dunes across each of the four counties (Figure 5:2).

Qualitatively, the factor score plots reveal patterns among the dune fields. The plot of the soil development variable appears to indicate that the soils on Tuscola County dunes are more developed than are the soils on the other three dune fields, with 13 of the 17 Tuscola dunes showing positive deviations from the mean (Figure 5:3). The second factor (texture) plot indicates that Tuscola dunes have a ratio of coarse sand to fine sand that is similar to that of Midland and Gratiot dunes (Figure 5:4). Arenac County dunes appear to have more fine sands than the other three dune fields, a relationship noted by Arbogast et al. (in press). The plot of the third factor (B, BC, C pH) plot indicates that these horizons in Tuscola dunes are more alkaline (Figure 5:5). The plotting of factor 4 (silt) is difficult to interpret. The factor scores appear to be fairly well distributed across the dune fields (Figure 5:6). Lastly, the map of factor 5 appears to indicate that Tuscola dunes may have more alkaline A horizons (Figure 5:7).

To test whether significant differences existed between the Gratiot, Midland, and Arenac dune fields, ANOVA and K-W tests were performed with each as a distinct subset (G vs. M vs. A). Both tests yielded identical results, identifying factor 2 (texture) as the only significant difference between the dune fields. An additional group of tests were performed to determine if the Arenac County dunes that had been identified as having some significant differences in field and laboratory data by Arbogast et al. (in press) are significantly different from Gratiot and Midland dunes based on PCA factors (A vs. G + M). Again, both tests yielded identical results, and identified factor 2 (texture) as the only

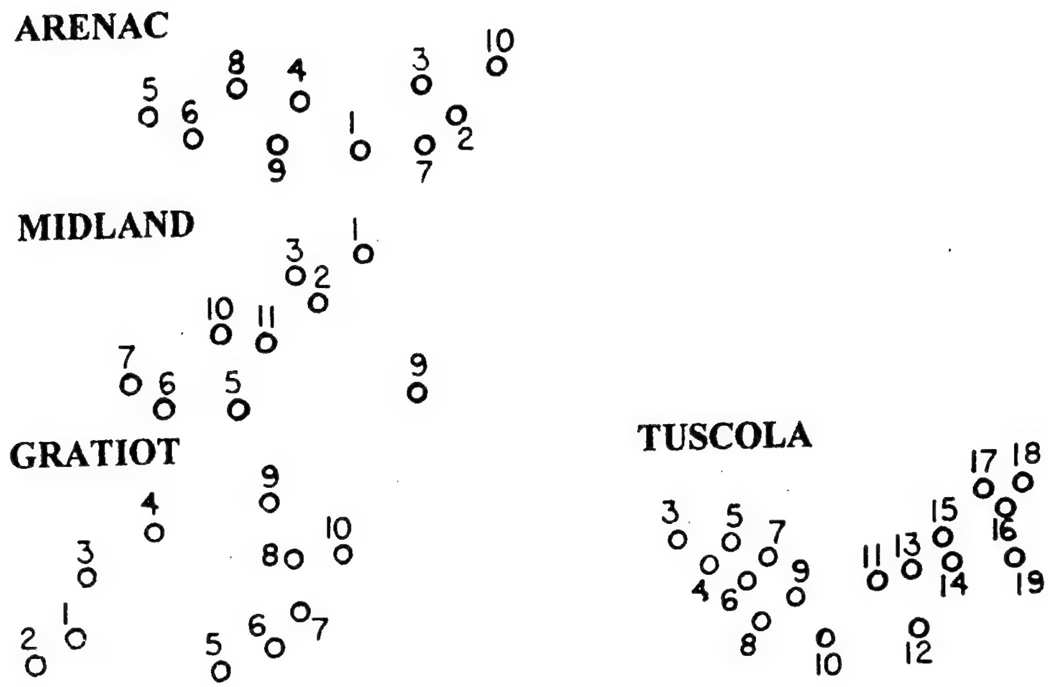


Figure 5 : 2 - Key to Dune Distribution Portrayed on Schematic Maps

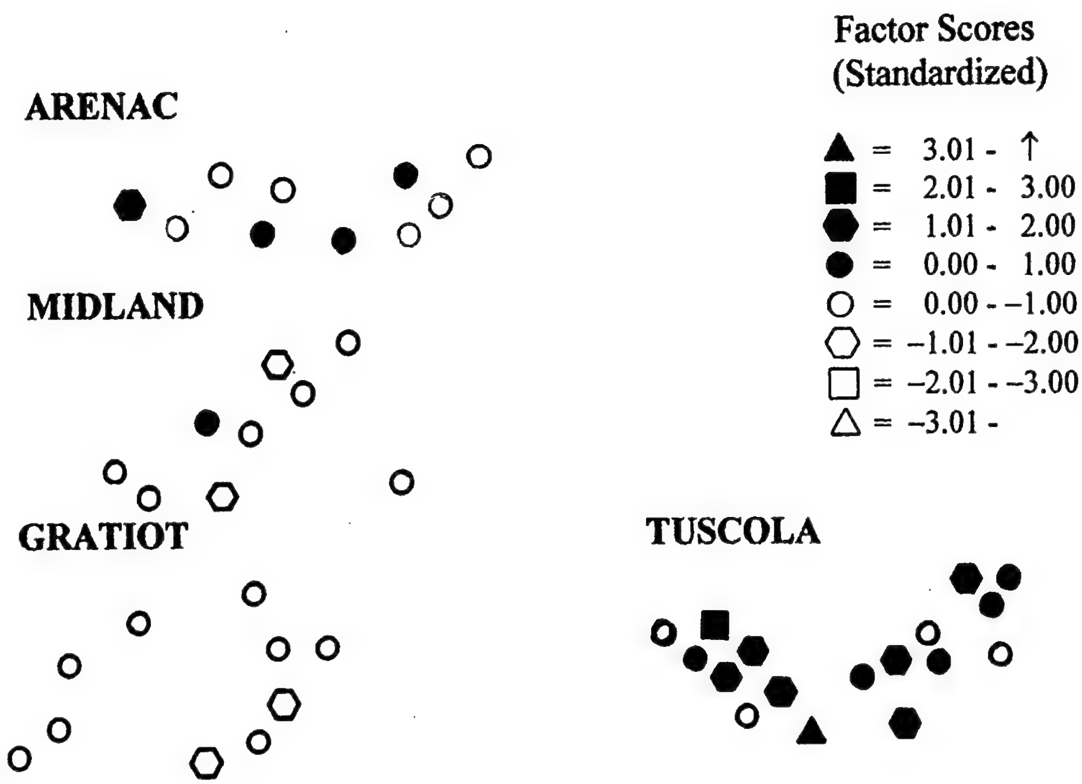


Figure 5 : 3 - Factor Score Plot - Factor # 1 - Soil development.

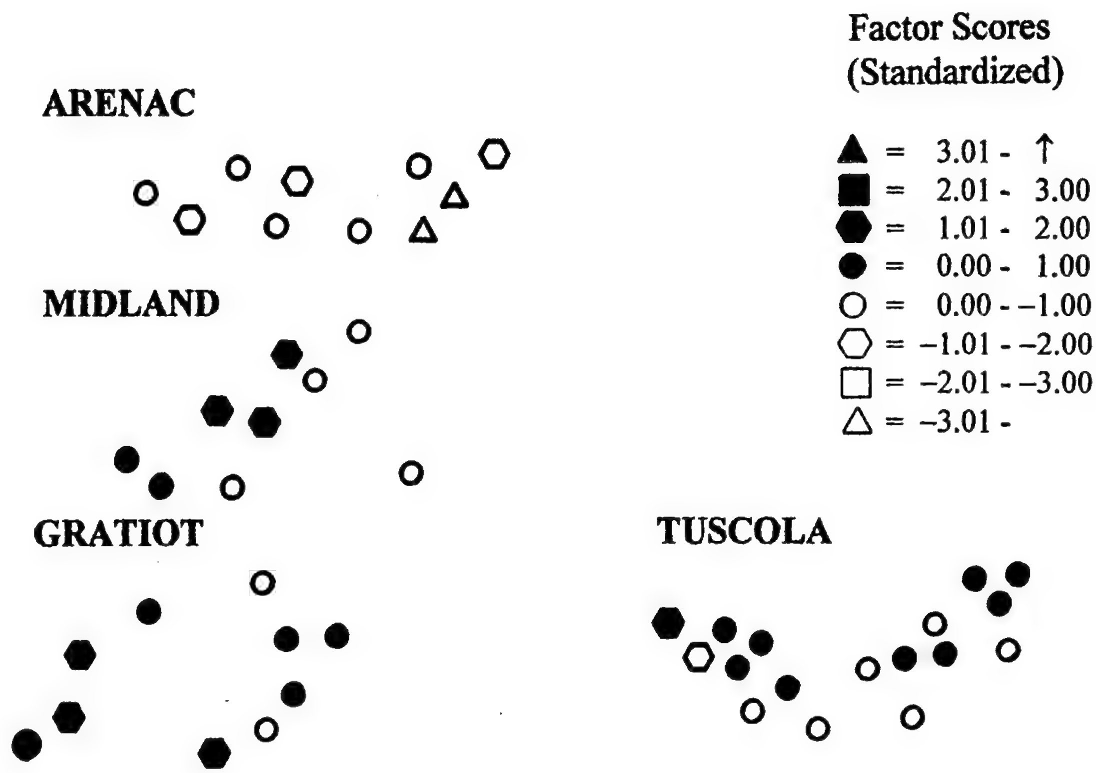


Figure 5 : 4 - Factor Score Plot - Factor # 2 - Texture.

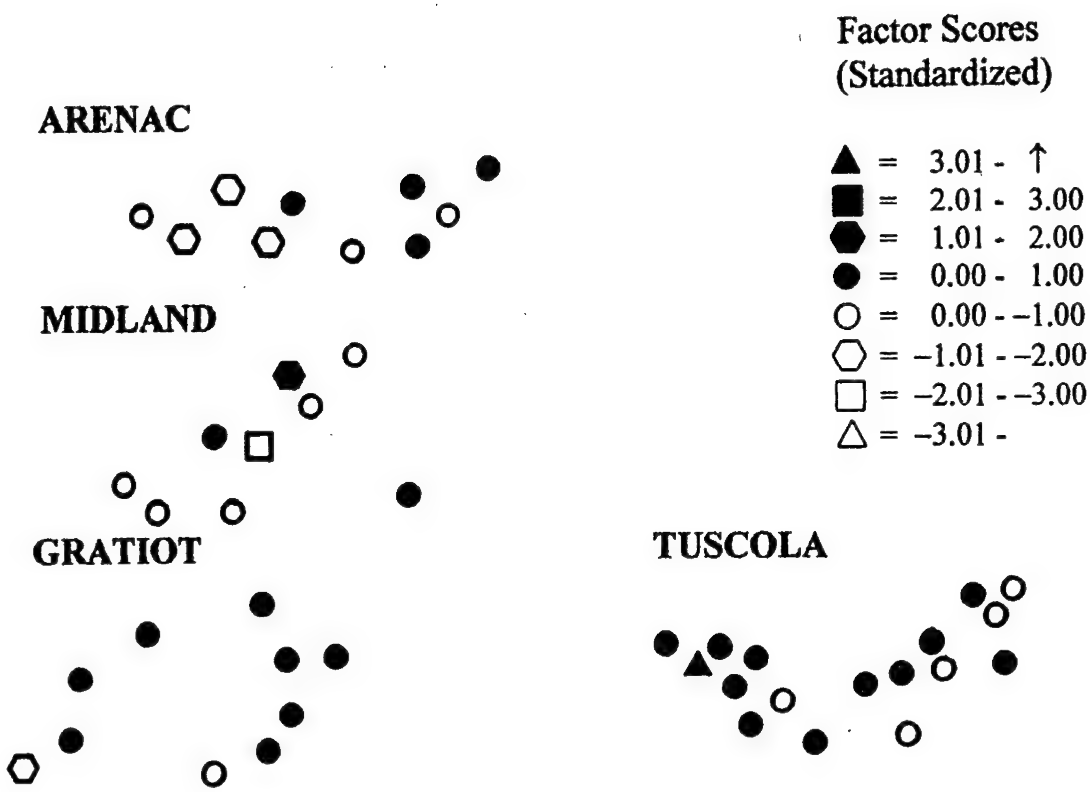


Figure 5 : 5 - Factor Score Plot - Factor # 3 - Subsoil pH.

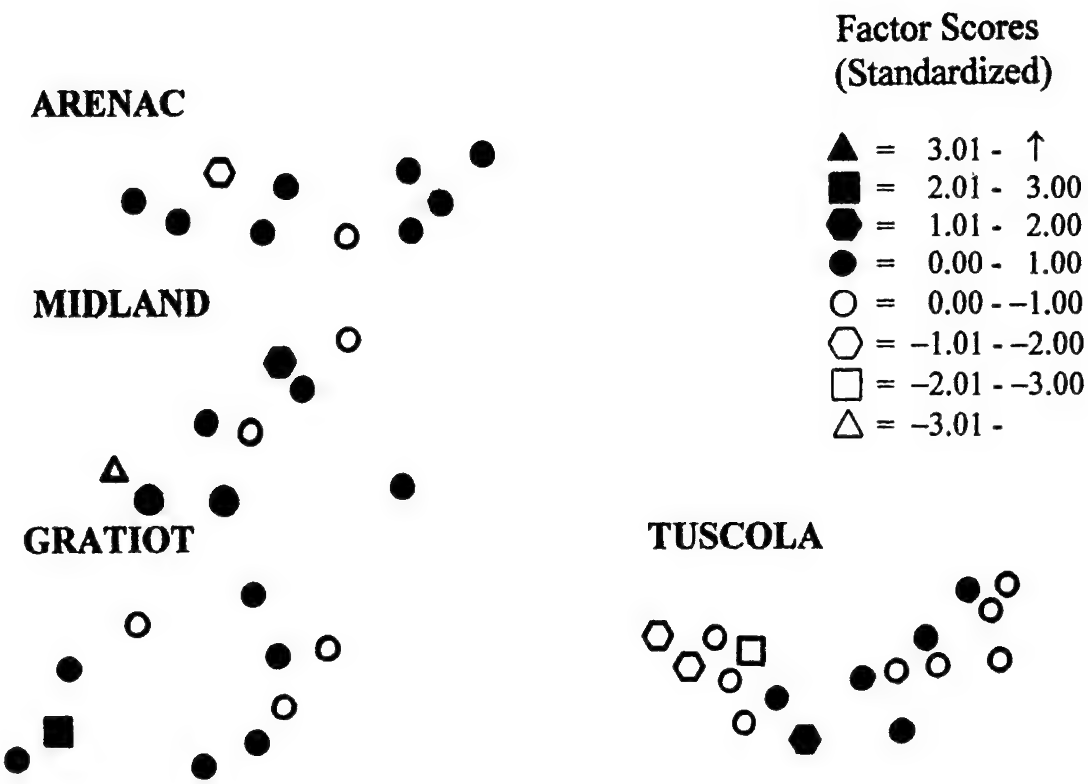


Figure 5 : 6 - Factor Score Plot - Factor # 4 - Silt.

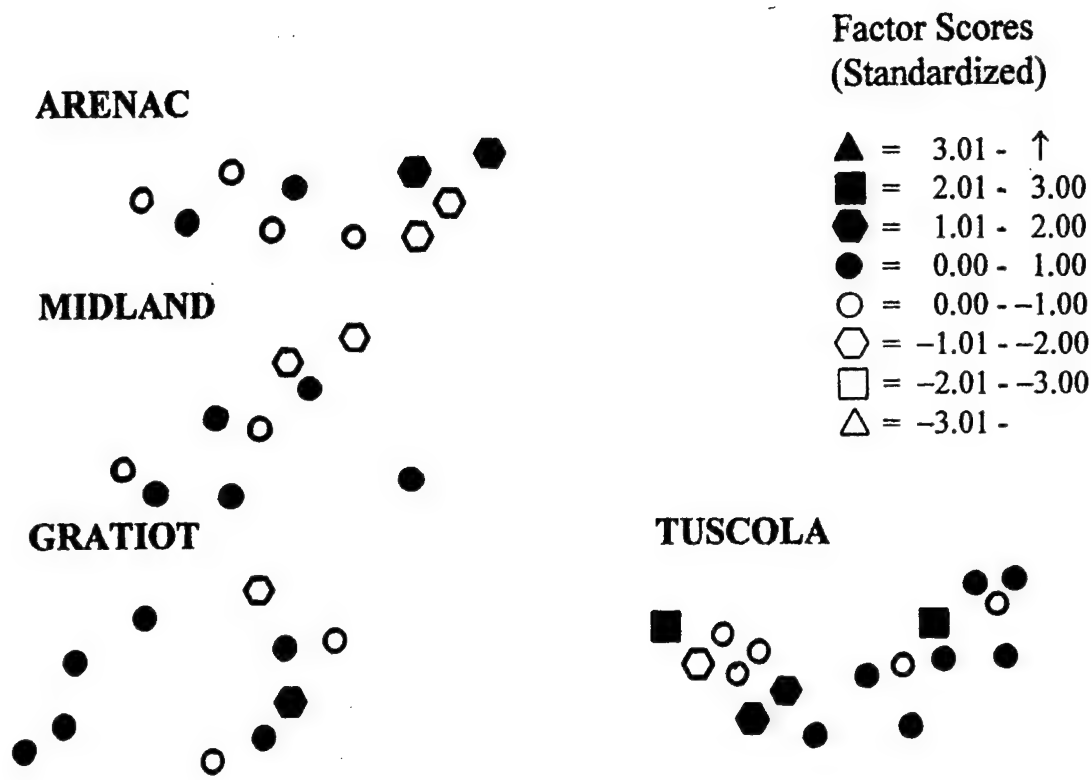


Figure 5 : 7 - Factor Score Plot - Factor # 5 - A horizon pH.

significant difference between the three dune fields. These results confirm the conclusion of Arbogast et al. (in press) that stabilization / pedogenesis began in the three dune fields at approximately the same time.

To assess whether significant differences existed between the four dune fields, tests were performed with each dune field as a distinct subset, Tuscola (T) vs Gratiot (G) vs Midland (M) vs Arenac (A). The results of ANOVA and K-W were identical, with significant differences present in factor 1 (soil development) and factor 2 (texture) (Table 5:6). To assess whether Tuscola dunes were significantly different from the other dune fields, tests were performed which compared two subsets: Tuscola vs the other dune fields as a group (T vs G+M+A). The results, although not in total agreement, indicated that Tuscola was significantly different in factor 1 (soil development) only (Table 5:6).

The analysis also demonstrated that the Tuscola dune field was not significantly different from the other Saginaw lowland dune fields in respect to factors 2, 3, 4, and 5, but was significantly different in respect to factor 1 (soil development). This suggests that the Tuscola dunes are more developed, and therefore probabily formed prior to the other Saginaw Lowland dune fields, assuming that the other four soil forming factors are not significantly different between all four dune fields.

Cluster Analysis

To further clarify the relationships delineated in the PCA and the examination of the factor scores, cluster analyses were performed to objectively group dunes with similar soil characteristics. Cluster analysis attempts to maximize within group similarity while minimizing between group similarity (Balling, 1984). Cluster analysis can simplify

Table 5 : 6 - Results of Significance Testing of Factor Scores

Relationship			ANOVA		Kruskal-Wallis
		Prob. Value	Sig. Diff. (p=0.05)	Prob. Value	Sig. Diff. (p=0.05)
T vs G vs M vs A					
Factor 1	Development	0.00	Yes	0.00	Yes
Factor 2	Texture	0.00	Yes	0.00	Yes
Factor 3	Subsoil pH	0.19	No	0.21	No
Factor 4	Silt	0.39	No	0.37	No
Factor 5	A horizon pH	0.19	No	0.29	No
T vs G+M+A					
Factor 1	Development	0.00	Yes	0.00	Yes
Factor 2	Texture	5.52	No	0.58	No
Factor 3	Subsoil pH	0.11	No	0.35	No
Factor 4	Silt	0.11	No	0.12	No
Factor 5	A horizon pH	0.03	Yes	0.06	No

complex patterns resulting from a set of observations or can help generate / reevaluate hypotheses (Everitt, 1980). In this study, cluster analyses are used to condense, simplify, and confirm the information contained on the factor-score plots.

Similar to PCA, cluster analysis requires several user decisions, including choice of variables, method of clustering, and determination of the number of clusters to retain (Winkler, 1992). In this study, the components identified in the PCA were used for the cluster analysis, and two methods of clustering were utilized: Ward's and Kmeans.

Ward's method produced hierarchical clusters, that joined the rows (the 46 individual dune soils) based on the columns (the 5 components). The clustering algorithm first determines how close observations are to one another by calculating either a similarity or distance matrix (Winkler, 1992). Euclidean distance is the most commonly used distance measure (Everitt, 1980) and was employed here. Various linkage methods were also examined. Based on trial and error, Ward's method was selected. Ward's method uses the average value of all the objects in a cluster as a reference point for distances to other objects or clusters, and adjusts for covariance (Ward, 1963). The final choice in Ward's method involves the procedure for choosing the optimum number of clusters from the linkage-tree diagram. No completely satisfactory procedure exists for making this choice (Winkler, 1992).

In this study, the number of clusters was based on an inspection of the resulting linkage tree and the rate of change of the multiple-squared correlation coefficients. This method resulted in the identification of six clusters on the linkage tree diagram (Figure 5:8), which were subsequently plotted on a schematic distribution of the dunes. The cluster plot

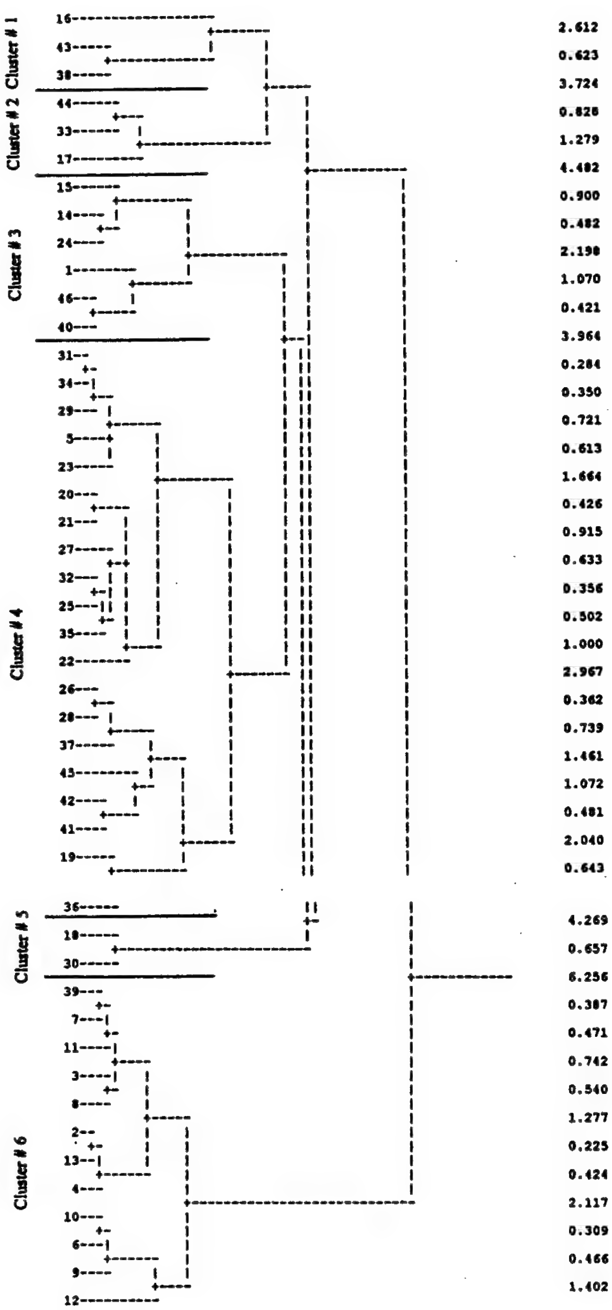


Figure 5 : 8 - Linkage Tree Diagram, cluster analysis (Ward's method)

clearly shows that the majority of the Tuscola dunes are similar (11 of 17 dunes), while the other three dune fields appear to group together (Figure 5:9).

To verify this conclusion a second clustering method, Kmeans, was employed. Kmeans is an iterative clustering process that splits a set of objects (in this case soils on dunes) into a selected number of groups by maximizing between-cluster variation relative to within-cluster variation (Wilkinson, 1992). User defined choices in Kmeans are limited to the number of variables to be analyzed and the number of clusters desired. In this study, the PCA data set was used and six clusters were requested. The resulting clusters were plotted on a dune distribution schematic and confirmed the results of Ward's clustering (Figure 5:10). A Tuscola dune group and a Saginaw dune group are clearly visible. Membership of individual dunes in the clusters is identical with the exception of only three dunes. In Ward's method dunes T4, A2 and A7 group together as one cluster: cluster #1. In the Kmeans method these three dunes were separated into two clusters, a T4 cluster, cluster #2, and a A2, A7 cluster, cluster #3. Table 5:7, a table of means and standard deviations for each factor, on each cluster, aids in the comparison of the two clustering methods.

While both cluster plots clearly show that a Tuscola dune group and a Saginaw dune group exist, the plots also show that some variability within each dune field also exists. In the interest of analyzing this within-group variability, the outliers within a particular dune field were examined. Germane to this study are the dunes within Tuscola County that failed to cluster within the Tuscola dune group, and any dunes in the other dune fields that clustered within the Tuscola dune group.

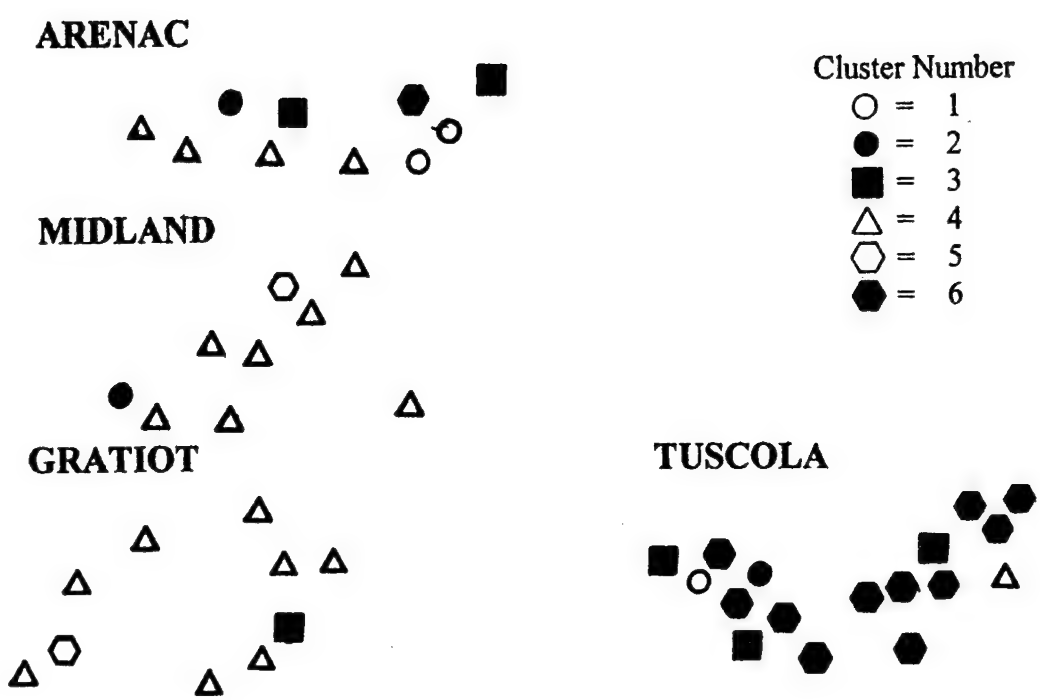


Figure 5 : 9 - Ward's Method Clusters.

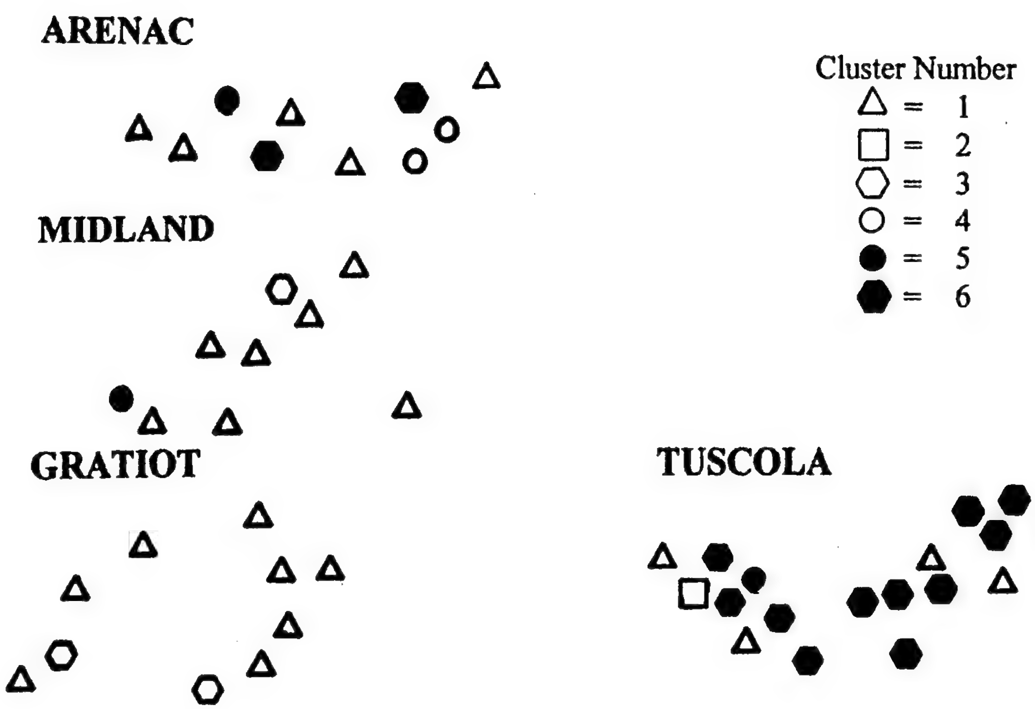


Figure 5 : 10 - Kmeans Method Clusters

Table 5 : 7 - Cluster Means and Standard Deviations

	Kmeans			**Join**		
Factor #	Cluster	Mean	Stand. Dev.	Equiv. Cluster	Mean	Stand. Dev.
1	1	-0.52	0.41	4	-0.485	0.529
2	1	-0.01	0.88	4	0.125	0.859
3	1	-0.08	0.77	4	-0.386	0.826
4	1	0.03	0.55	4	0.123	0.418
5	1	0.35	0.96	4	-0.138	0.634
1	2	0.26	0	1	-0.206	0.422
2	2	-1.02	0	1	-2.091	0.954
3	2	3.87	0	1	1.453	2.184
4	2	-1.8	0	1	-0.193	1.397
5	2	-1.2	0	1	-1.248	0.069
1	3	-1.04	0.4	5	-0.873	0.566
2	3	1.69	0.18	5	1.81	0.089
3	3	0.78	0.78	5	1.271	0.622
4	3	1.62	0.72	5	2.113	0.29
5	3	-1.44	0.52	5	-1.747	0.527
1	4	-0.44	0.13	1	-0.206	0.422
2	4	-2.63	0.23	1	-2.091	0.954
3	4	0.25	0.63	1	1.453	2.184
4	4	0.61	0.11	1	-0.193	1.397
5	4	-1.27	0.05	1	-1.248	0.069
1	5	-0.15	0.86	2	-0.155	1.05
2	5	0.27	0.37	2	0.266	0.452
3	5	-0.73	0.84	2	-0.725	1.029
4	5	-2.55	0.6	2	-2.546	0.733
5	5	-0.89	0.05	2	-0.894	0.063
1	6	1.29	0.69	6	1.342	0.727
2	6	0.05	0.4	6	0.117	0.343
3	6	-0.2	0.72	6	-0.053	0.555
4	6	0.21	0.5	6	0.188	0.541
5	6	0.17	0.62	6	0.249	0.619

In both the Ward's and the Kmeans clustering methods, 6 Tuscola dunes (T3, T4, T7, T8, T15, T19) failed to join the Tuscola cluster. While both methods agreed that Arenac dune A3 clusters with the Tuscola cluster. Dunes T3, T4, T8, T15, and T19 failed to join the Tuscola cluster because they exhibited the least amount of movement of Fe and Al of any of the Tuscola dune soils. In contrast, the Tuscola dune group is generally characterized by significantly more movement of Fe and Al relative to the other dune groups. Dune T7 failed to join because the soil had the most acidic B horizon sampled in Tuscola County, whereas most of the soils in the county are alkaline. Dune A3 clustered with the Tuscola dunes because of it's very thick B horizon and solum, alkaline A horizon, and it's high amounts of Fe and Al movement.

The variability of the dune soils, highlighted by PCA and cluster analysis, can be viewed from two perspectives; the traditional reductionist view, that variability can be explained with more and better measurements, and a dynamic view that variability is a outcome of complex system dynamics (Phillips et al., 1996). The sample sizes used, 10 dunes in each of Gratiot, Midland, and Arenac Counties, and 19 dunes in Tuscola, are admittedly small. Moreover, only a single pedon was sampled on each dune. As a result, there is some risk that the modal pedon may not have been sampled and soil variability is caused by unknown factors. PCA and cluster analysis indicate, however, that outliers resulted solely due to differences in soil pH and Fe and Al movement.

It is possible that slight differences in the effects of vegetation could be responsible for the variations. Numerous studies have documented the effects that trees with large crowns and stem diameters have on the morphology and chemistry of the soils that lie below them (e.g. Crampton, 1982; Johnson et al., 1979; Gersper et al., 1970; Zinke,

1962). These studies have demonstrated an influence of concentrated rainfall water via stemflow on podzolization near the stems. With the primeval coniferous forests removed by logging over 120 years ago, ensuring uniformity in vegetation was impossible. Clearly however, the general trend in the cluster analyses show the presence of two distinct groupings of dunes on the Saginaw Lowlands, a Tuscola group, and a Gratiot, Midland, Arenac group. Moreover, the variability is significant only with regard to soil development.

Relative Dating of the Tuscola County Dune Field

The degree of soil development in Spodosols has been successfully related to soil age in Michigan (Franzmeier and Whiteside, 1963b; Barrett and Schaetzl, 1992; Arbogast et al., in press, Arbogast, unpublished data). Thus, morphological and chemical properties of Spodosols can be used as relative-age-dating tools. Such properties include the type of horizons present, the thickness of horizons, solum thickness, accumulated Fe and Al in the B horizon, and the POD Index. In Michigan, most of the research employing Spodosols as relative-age-dating tools has occurred in northern Michigan (e.g., Franzmeier and Whiteside, 1963b; Barrett and Schaetzl, 1992), where podzolization occurs at an accelerated pace relative to lower Michigan (Schaetzl and Isard, 1991). Franzmeier and Whiteside (1963b) for example, concluded that an E horizon begins to form in 2,250 years, whereas a Bs and Bhs horizons requires 3,000 and 8,000 years to develop, respectively. In support of Franzmeier and Whiteside (1963b), Barrett and Schaetzl

(1992) concluded that between 4,000 to 10,000 years were required for the formation of a Bs horizon.

Research utilizing Spodosols as relative "age" dating tools in central and southern Michigan has only recently begun, and a lack of radiometric dates taken from Spodosols has made it difficult to gauge the pace of podzolization in the region. On the Saginaw Lowlands, Arbogast et al. (in press) compared the morphology and chemistry of the dune soils in Gratiot, Midland, and Arenac Counties to the studies of Spodosols of northern Michigan and concluded that dunes were stabilized ≥ 4,000 yrs. B.P.

In this study, principal components analysis and the resulting factor score plots demonstrated that soils significantly differ between Tuscola County, as one group, and Gratiot, Midland, and Arenac Counties as another group. The primary variable, which explained most (28%) of the variance, was attributed to differences in soil development, with soils in Tuscola County being better developed. The two cluster analyses confirmed the existence of two distinct populations within the lowland dunes, a Tuscola group and a Gratiot, Midland, and Arenac group. Parametic difference of means tests (ANOVA) and the equivalent non-parametric tests (K-W) demonstrated that while only slight differences in parent material exist between the two groups, the Tuscola group contains soils that are significantly more developed. The Tuscola dune soils are more developed even with a more alkaline parent material, which slows the speed of podzolization (e.g., Stobbe and Wright, 1959; Peterson, 1976; Birkland, 1984). With qualitative comparisons of climate, organisms, and relief indicating general uniformity between groups, and only a slight statistical difference in parent material, the greater degree of development of Tuscola dune

field soils can best be explained by a difference in the soil forming factor of time. Thus, it is concluded that Tuscola dunes stabilized sometime prior to dunes in Gratiot, Midland, and Arenac Counties.

Dune and Wind Orientations

The windrose diagram for Flint, Michigan (Figure 5:11) is a graphical representation of the potential magnitude and direction of sand drift based on current (1966-75) wind direction, frequency, and magnitude. The diagram assumes that the sand to be moved is dry, has no stabilizing vegetative cover, and has a mean textural size in the medium sand (0.25 -0.50 mm) range. Medium sand dominated 207 of the 236 total horizons examined in both studies (Table 5:1; see Arbogast et al., in press). The Flint windrose shows that if dunes formed in the region under the present wind regime, they would have southwesterly-oriented (225°) limbs and a resultant drift direction to the northeast (56°).

Dune-axis-orientation roses from the dunes sampled in Gratiot, Midland, and Arenac Counties indicate that the limbs on these dunes have a modal range in orientation from west/northwesterly (292°) in Gratiot and Midland Counties, to northwesterly (315°) in Arenac County. The sand-rose diagram constructed for Tuscola County shows a modal orientation identical to that of Gratiot and Midland dunes(i.e. west/northwesterly or 292°; Figure 5:12).

In an effort to determine whether any statistically significant differences exist in dune orientation between the dune fields, ANOVA and K-W tests were performed. First, dune

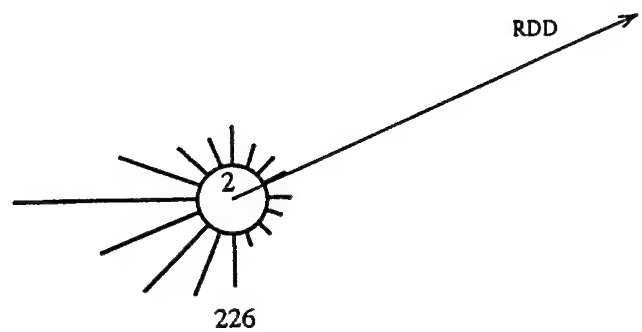


Figure 5 : 11 - Wind Rose for Flint, Michigan. RDD, resultant drift direction. Numerical value within circle is the reduction factor, whereas the value below the circle is the drift potential in vector units (see Fryberger and Dean, 1979, for details).

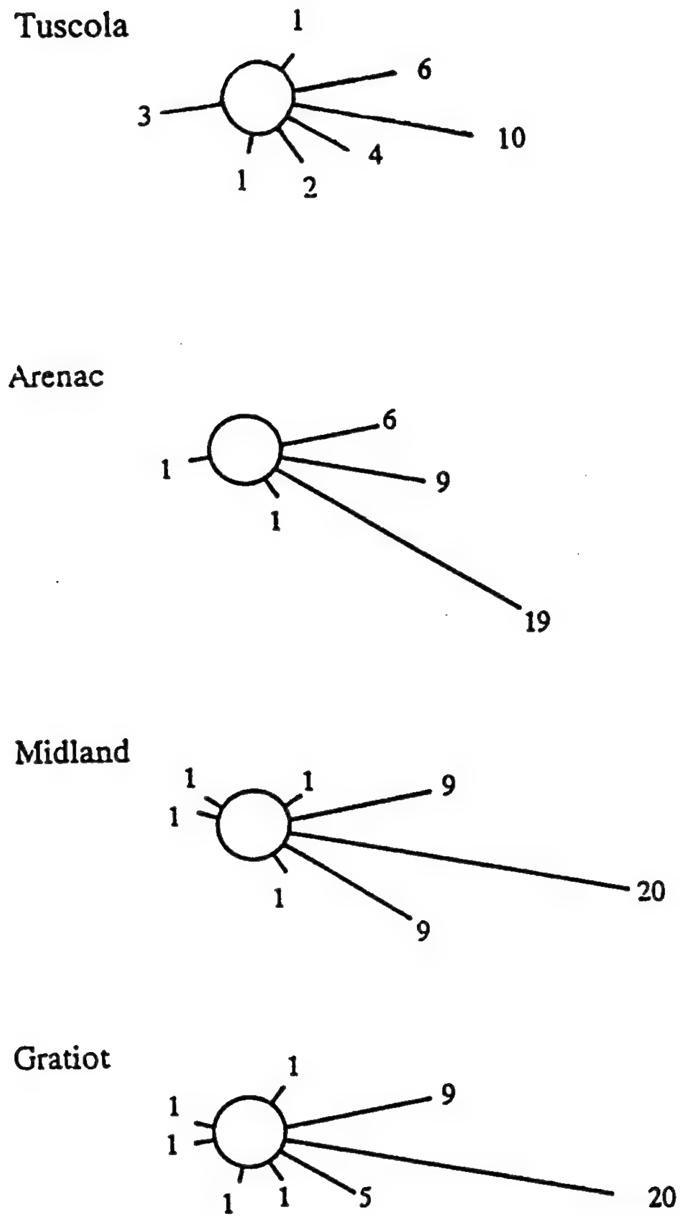


Figure 5 : 12 - Dune Orientation Roses - Saginaw Lowland dune fields (Modified from Arbogast et al., in Press). Diagram depicts the orientation of the limbs of all identifiable parabolic dunes within an eight kilometer radius around the centroid of each study area. Lengths of the arms are proportional to frequency of occurrence. Long arms in the SE direction implies that the dune had limbs oriented toward the NW.

orientation data had to be converted from a sixteen quadrant cardinal direction system, a circular number scheme wherein 0° and 360° are equal, to a natural number system. An examination of dune orientations revealed that no dunes had axes in three of the southern quadrants, from 135° to 202.5°. Therefore, these quadrants made a natural break from which the linear number sequence could begin. Moving in a clockwise pattern, the remaining 13 quadrants were renumbered from 1 to 13.

Results from ANOVA found no significant differences in dune orientation between Gratiot, Midland, and Arenac (G vs. M vs. A Counties) nor between Tuscola and the other three dune fields (T vs. G+M+A). K-W tests produced one differing result, finding that a significant difference does exist between Arenac and Gratiot/Midland (A vs. M+G). Arbogast et al. (in press) could not explain the difference in Arenac's dune orientations, but were not convinced that it was an important distinction between the dune fields. Clearly, however, the orientation of the dunes suggests that no dune forming winds came from the south, and that Tuscola dunes formed generally under the same prevailing winds as the other Saginaw dune fields. Moreover, these paleowinds are different from those of the present, southeasterly (see Figure 5:11).

Paleoclimatic Interpretations

The geomorphic history of dunes in Tuscola County has numerous paleoclimatic implications. Today the landscape of the Tuscola County dune field is forested, with many swampy interdune areas. As a result, the dunes are stable. For widespread mobilization of eolian sand to have occurred, however, the landscape must have had less vegetation. Thus, it would seem likely that the period of landscape destabilization that led to the

formation of these dunes was drier than present (e.g., Ahlbrandt et al., 1983; Grigal et al., 1976; Muhs, 1985; Holliday, 1995).

As previously noted, the dunes overlie late-Wisconsin glacio-lacustrine deposits, suggesting evolution in a newly deglaciated environment. Conditions would theoretically have been favorable for eolian mobilization during a brief interval of time following the recession of the glacial lake waters and before the invasion of stabilizing vegetation (e.g. David, 1981; Filion, 1987; Thorson and Schile, 1995). Lake Saginaw receded from the Cass River valley and the study area became subaerial at approximately 12,800 B.P. (Eschman and Karrow, 1985). Thus, the dunes may be Late Pleistocene landforms.

The dunes are oriented generally to the northwest (e.g. Figure 5:12), however, an orientation not observed where dunes formed close to the ice margin elsewhere (David, 1981; Filion, 1987; Thorson and Schile, 1995). Late-Pleistocene winds, near the ice sheets, are hypothesized to have been easterly to northeasterly (Kutzbach et al., 1993). Thorson and Schile (1995), in their examination of late-Pleistocene dunes in Connecticut, concluded that northeasterly winds prevailed in the region until approximately 11,000 yrs. B.P. Thus, the orientation of the dunes in Tuscola County favors a period of mobilization sometime after 11,000 yrs. B.P. Dunes in northeastern Minnesota, which formed between 8,000 and 5,000 yrs. B.P. (Grigal et al., 1992), and dunes in the upper peninsula of Michigan, which probably formed between 10,000 and 4,000 yrs. B.P. (Arbogast, unpublished data), have northwesterly-oriented limbs similar to the Tuscola dunes.

Soil data can be used to refine the age estimate of the Tuscola dunes further. The data strongly suggest that the dunes are older than the other Saginaw dune fields. According

to Arbogast et al. (in press), the Saginaw dunes contain Bs horizons which take at least 4,000 years to form in northwest lower Michigan (Barrett and Schaetzl, 1992), but lack Bhs horizons, which, as noted above, require at least 8,000 years to form. Tuscola dune soils have a better developed spodic morphology than the other Saginaw dune fields but also lack Bhs horizons. The paleowind and pedologic data suggest that the Saginaw dunes stabilized prior to 4,000 yrs. B.P., and probably before 10,000 yrs. B.P. (Arbogast et al., in press), while the Tuscola dunes probably stabilized sometime during the early to middle Holocene, 8,000 to 4,000 yrs. B.P.

Data exist supporting eolian activity in the early to middle Holocene in Michigan. Zumberge and Potzger (1956) have suggested that regional drying may have occurred in the Saginaw Bay area in conjunction with the dramatic lowering of lake levels in the Michigan and Huron Basins during the early and middle Holocene. In the Huron basin, lake level reached its lowest point (110 meters below the present level) 10,000 yrs. ago and was not at present levels for 5,000 years (Eschman and Karrow, 1985). Arbogast et al. (in press), suggested that these decreased lake levels may have lowered the regional water table in the Saginaw Lowlands, reducing soil moisture and leading to more frequent forest fires that could have promoted landscape destabilization.

Regional paleoclimate data suggest that early- to mid-Holocene landscape destabilization occurred in the Midwest and may have also occurred in lower Michigan. The effects of this destabilization are manifested in the geomorphic systems of the region. On the Great Plains, Ahlbrandt et al. (1983) and Muhs (1985) reported dune activity in the mid-Holocene, followed by soil formation from approximately, 5,000 - 3,500 yrs. B.P. In

Minnesota, Grigal et al. (1976) suggested that a more arid climate, incapable of supporting forest dominated the state from 8,000 - 5,000 yrs. B.P., while Keen and Shane (1990) reported three eolian episodes, between 9,100 - 4,000 yrs. B.P, each characterized by drought and a decrease in forest cover. If the dunes in Tuscola did form during the early or middle Holocene in a pulse of eolian activity that was earlier than the other Saginaw dune fields, then the effect of mid-Holocene warming was more widespread than previously thought.

SUMMARY AND CONCLUSIONS

This investigation has examined the previously unstudied dunes, located in the Deford State game Area of Tuscola County, in the southeastern part of the Saginaw Lowland. The dunes are parabolic, have northwesterly-oriented limbs, and overlie glacio-lacustrine sediments approximately 12,000 years old. Thus, the dunes must be post-glacial landforms. Hypothetically, these dunes stabilized concurrently with the dunes studied by Arbogast et al. (in press) to the northwest. In testing this hypothesis, 19 surface soils (Entic Haplorthods) were morphologically and chemically analyzed on dune crests and compared to the surface soils in the other dune fields. The soils are similar with A/E/Bs/BC/C horizonation. POD (morphologic) indices are ≤ 2 and textural data indicate parent material uniformity. Parametric difference of means tests (ANOVA) and the non-parametric equivalent tests (K-W) demonstrated that the Tuscola dune soils are slightly more alkaline and demonstrate significantly ($p=0.05$) more accumulation of Al and Fe in their spodic (Bs) horizons.

Principal components analysis was employed to reduce the number of redundant variables and to reveal five structural elements (factors) that explained the variation within the data set. The subsequent plotting of factor scores revealed qualitative patterns among the dune fields, indicating that dune soils in Tuscola County are more developed than the other three Saginaw Lowland dune fields.

To further clarify the relationships, cluster analyses were performed to objectively group dunes with similar soil characteristics. Although some variation in the resulting dune group clusters occurred, the cluster plots clearly showed the existence of two dune

groups on the Saginaw Lowlands, a Tuscola group and a Gratiot, Midland, and Arenac dune group.

In addition to the soils data, the orientation of the dunes was also examined. The comparison of dune orientation with wind regime demonstrated that the dunes formed under a regime different from both the present (southwest) and that hypothesized for the late-Pleistocene (northeast; Kutzbach et al., 1993). The dunes are oriented to the northwest, which is similar to that responsible for dune formation in forested regions of North America between 8,000 and 5,000 yrs B.P. (e.g., Grigal et al., 1992).

In conclusion, relative-age, and geomorphic data suggest that a period of eolian sand mobilization and stabilization has occurred in the Tuscola County dune field during the Holocene. This period of instability and subsequent stability, as suggested by soils and wind data, occurred during the early or middle Holocene, but shortly before the stabilization of the other Saginaw lowland dune fields. The period of mid-Holocene warmth and dryness (e.g., Grigal et al., 1976; Ahlbrandt et al., 1983; Muhs, 1985; Keen and Shane, 1990), which probably influenced lower Michigan, coincides with a period of dramatically lower lake levels in the Michigan and Huron basins (Eschman and Karrow, 1985).

While these speculations certainly need to be reinforced through extensive radiometric dating of the dunes within the region, they clearly contribute to our understanding of the timing and causes of Holocene eolian sand mobilization in forested regions of North America. Paleoenvironmental data derived from this study will contribute to a large-scale data set focusing on post-glacial landscape change in Michigan.

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